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A review of integrated solar combined cycle system (ISCCS) with a parabolic trough technology

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A B S T R A C T

The huge amount of solar energy available on Earth's surface has heightened awareness in Concentrating Solar Power, and more particularly in hybrid concepts. The integrated solar combined cycle system (ISCCS) is one of the more promising hybrid configurations for converting solar energy into electricity and it might become the technology of choice in the near future. This article reviews the R&D activities and published studies since the introduction of such a concept in the 1990s. The review includes the current status and describes different hybridizations of solar energy with natural gas, coal and other renewable energy sources. Furthermore, it provides in-depth analysis of real and expected R&D finding.

Contents

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1. Introduction

The economic boom in developing countries, particularly China and India, and the continuous increase in world population are the major factors that have boosted energy demands and prices [1,2]. This has resulted in the worsening of the world environmental problems such as climate change and global warming [1–4]. This has also put stress on the energy resources with hike in prices and risk in shortage and depletion. Recent estimates have indicated that the remaining recoverable resources are about 2670 billion barrels of conventional hydrocarbons including crude oil and natural gas [1]. This will not be enough to meet world energy needs by 2050 and will definitely result in shortage with onerous energy costs for end-users.

To preserve the limited resources and to address raising energy security and environmental concerns R&D activities for the development of efficient and sustainable energy systems have been booming. To this end, three issues have been the object of intense focus [4–12]

energy efficiency improvements and low-carbon technologies,
technologies advancements including scaling up, and
renewable energy technologies.

Increasing penetration of low-carbon technologies and enhancements in the thermal efficiency of fossil-fuelled power plants can keep up the energy demand growth while technology advancements mitigate high energy costs. Renewable, in particular solar, energy has the potential of meeting the world energy needs while addressing energy security and environmental concerns. Nevertheless, technological advances in renewable energy electricity production are necessary before renewable electricity becomes competitive with conventional technologies. For instance, polygeneration power plants can produce electricity with thermal efficiency over 60% while solar only power station cannot exceed 30%. This results in higher costs. To solve this issue, hybrid concepts that join the advantages of the three above mentioned issues have been proposed. Among all the renewable technologies available for hybridization, Concentrating Solar Power (CSP) is one with the potential to make major contributions of clean energy with higher efficiency because of its relatively conventional technology and ease of scale-up [13–19].

At present, the most proven CSP technology for hybridization is the parabolic trough. Hybridization can be done in numerous ways including the use of an auxiliary firing or a fossil back-up in the thermodynamic cycles [20,21]. Earlier, in the 1980s, a total of nine Solar Electric Generating Systems (SEGSs) have been built in the southern California desert. Each plant has used a solar field with a Parabolic Trough Technology (PTT) to heat up an Oil-HTF. The thermal energy in the oil has been used to generate steam to power a Rankine cycle. Later on, in the 1990s, and in order to enhance solar-to-electricity conversion efficiency, the integration of PTT into a modern combined cycle has been proposed by Luz Solar International. This advanced concept is known as the integrated solar combined cycle system (ISCCS). The ISCCS commonly consists of a conventional Combined Cycle (CC), a solar field, and a Heat Solar Steam Generator (HSSG). In the last decade, R&D activities and implantation of this type of power plants have been supported by grants awarded by the Global Environment Facility to some developing countries. For this reason, various feasibility studies and costs assessments have been carried out along with thermal performance prediction that investigate the ISCCSs in operation, underway or in the planning stage all around the world, particularly, in Algeria, Egypt, Morocco, Mexico, the US, Iran, China, and Italy.

The present paper is a chronological review of the ISCCS with a parabolic trough technology, highlighting its current status around the world, identifying its different configurations, and pointing out the key findings of R&D activities that have been published.

2. Current status and projects around the world

2.1. Operational ISCCSs

Nowadays several integrated solar combined cycle power plants are operating all around the world. In North Africa, three power plants are already in operation in Algeria (Hassi R'Mel, 150 MW, with 20 MW solar), Morocco (Aïn Beni Mathar, 470 MW, with 20 MW solar), and Egypt (Kuraymat, 140 MW, with 20 MW solar). In Iran, the Yazd ISCCS has been commissioned in August 2010 (Yazd, 467 MW, with 17 MW solar). In Italy, the Archimede solar power station, with smaller solar field, has been operating since July 2010 in Priolo Gargallo. In the US, the largest ISCCS, Martin Next Generation Solar Energy Center, has been inaugurated in December 2010. Table 1 and 2 provide more details about the ISCCSs that are in operation worldwide.

2.1.1. Hassi R'Mel [22–25]

The Hassi R'Mel ISCCS consists of a 130 MW combined cycle and a 25 MW parabolic trough solar field that covers an area of over 180,000 m^2. The plant is located in Tilghemt, Hassi R'Mel. The solar field is composed of 216 solar collectors in 54 loops with an inlet heat transfer fluid temperature of 290 °C and an outlet temperature of 393 °C. This project has been promoted by Solar Power Plant One (SPP1) in build-own-operate contract mode over a 25 year-period for Sonatrach. The SPP1 is a joint venture between Abener and New Energy Algeria NEAL. The project has been developed by NEAL, a joint venture between Sonatrach,

Table1
Operational ISCCSs [31,36].

Project/plant name	Company/ Owner	Technology	Country	Location	Capacity (MW)	Solar Elec. (MW)	Starting date	Coordinates
Aïn Beni Mathar	ONE	Natural gas-ISCCS	Morocco	Ain Beni Mathar	470	20.00	May 2011	34° 4′ 12.36″N 2° 6′ 18.972″W
Hassi R'mel	Abener/Sonatrach	Natural gas-ISCCS	Algeria	Hassi R'mel	150	20.00	July 2011	32° 55′ 48.72″N 3° 16′ 5.88″E
Kuraymat	NREA	Natural gas-ISCCS	Egypt	Kuraymat	140	20.00	July 2011	29° 16′ 43.68″N 31° 14′ 56.04″E
Martin Next Generation Solar Energy Center	Florida power and light	Natural gas-ISCCS	US	Indiantown, Florida	3780	75.00	December 2010	27° 3′ 4.32″N 80° 33′ 7.2″W
Termosolar Borges	Abantia, Comsa Emte	Renewable-ISCCS	Spain	Borges Blanques, Lleida	22.5	–	December 2012	41° 31′ 43.68″N 0° 48′ 16.42″E
Archimede	Enel	Natural gas-ISCCS	Italy	Priolo Gargallo	750	5.00	14 July 2010	–
Yazd	IEDO [37]	Natural gas-ISCCS	Iran	Yazd	467	17.00	August 2010	31° 57′ 48.24″N 54° 3′ 53.64″E

(–) Not available.

Table 2
Solar field design data of operational ISCCSs [31,32,36].

Solar field	Solar collector assemblies	Number of SCAs	Reflective surface	Reflecting area	Solar receiver	Heat transfer fluid
Aïn Beni Mathar	Abengoa Solar Astro	224	Rioglass	183,120 m^2	Schott PTR70	Therminol VP-1
Hassi R'mel	Abengoa Solar Astro	216	Rioglass	183,120 m^2	Schott	Thermal VP-1
Kuraymat	Flagsol SKAL – ET 150	160	Flabeg RP3	130,800 m^2	Schott PTR70	Therminol VP-1
Martin Next Generation Solar Energy Center	Gossamer Space Frames LAT 1	–	Rioglass	190,000 units	Solel UVAC2008	Dowtherm A
Termosolar Borges	Siemens	336	Rioglass	181,000 m^2	Siemens UVAC2010	–
Archimede	Siemens	–	Rioglass	3000 m^2	Siemens UVAC2010	Molten salt

(–) Not available.

Sonelgaz and SIM. The construction contract has been signed on January 5, 2007. The power plant was commissioned on June 2011 and inaugurated on July 14, 2011. To meet its needs, Sonatrach is acquiring all of the ISCCS electrical generated power at the cost of 0.04$ kW/h.

2.1.2. *Kuraymat [26,27]*

The Kuraymat power plant is located 90 km south of Cairo and about 2.5 km from the eastern shore of the Nile. The Kuraymat ISCCS is made up of 140 MW combined cycle and a solar field of about 61 MWth at the design point. The field consists of 1920 modules in 160 collectors with an overall reflecting surface of about 131,000 m^2. In order to reduce wind effects, wind breakers have been installed on the two wind dominating direction sides. The project is owned by the New and Renewable Energy Authority of Egypt (NREA). The German Fichtner Solar Company has acted as the engineering interchange between the EPC Contractor of the Combined Cycle, the Spanish Iberdrola and the EPC Contractor of the solar field, the Egyptian Orascom CI. The technology provider has been Flagsol, a subsidiary of Solar Millennium. The plant has been put into operation in July 2011. It has been really positive as experiments have pointed out that the solar field can generate nearly 8% more energy on average than estimated.

2.1.3. *Aïn Beni Mathar [28]*

The Aïn Beni Mathar hybrid solar power plant is situated in the eastern part of Morocco. It is located about 88 km south of the city of Oujda, at northern latitude of 34°4′ and a western longitude of 2°6′ and at an elevation of 923 m. It combines the advantages of the 470 MW combined cycle plant with those of the 20 MW parabolic trough solar field of more than 180,000 m^2. The combined cycle has higher flexibility since it is made up of two gas turbines producing 150 MW each and a 150 MW steam turbine. The project has been developed for the state-owned electricity utility, Office National de l'Electricité (ONE). Abener, Abengoa Solar and Teyma have designed, constructed and commissioned the plant under the terms of a turnkey contract with ONE. The EPC contractor has been Abener Energia, which also operates the plant together with ONE. The plant has been put in operation in May 2011.

2.1.4. *Yazd [29,30]*

Yazd ISCCS has been constructed over a 900 ha land at KM 33 of Yazd–Khazarabad Road. It is world's first integrated solar combined cycle system and the eight largest solar power plant in the world. The Yazd power plant consists of two V94.2 gas turbines each with 159 MW capacity, a 143 MW capacity no-reheat two pressures steam turbine unit and a solar thermal unit with 17 MW capacity. The feasibility study of Yazd power plant has began in 2003 by Iranian experts with the association of German consultant researchers and engineers.

2.1.5. *Martin Next Generation Solar Energy Center [31]*

The Martin Next Generation Solar Energy Center ISCCS is located in western Martin County, Florida; just north of Indiantown. Its combined cycle is the 3705 MW Martin County Power Plant, which is currently the single largest fossil fuel power plant in the US. The plant has been constructed by Florida Power & Light Company (FPL). The EPC contractor for the project has been the Lauren Engineers & Constructors. The breaking ground was in December 2008 and the completion in December 2010.

2.1.6. *Termosolar Borges [31,32]*

The Termosolar Borges plant is located in the north-east of Spain, near the biomass combustion units that produce about

70 t/year. Its solar field consists of 336 collectors of a total reflective surface of 181,000 m^2. The plant has been promoted by the Spanish companies Comsa Emte and Abantia and has costed about €153 million. This renewable power station has been delivering up to 98,000 MWh/year with an operation of about 6500 h/year. It is supplying enough electricity for 27,000 households and allowing the void of 24,500 t of CO_2.

2.1.7. Archimede [31–35]

The Archimede integrated plant is located in Priolo Gargallo near Syracuse in Sicily, Italy. It has been owned and operated by Enel. It has been developed by ENEA and Archimede Solar Energy, a joint venture between Angelantoni Industrie and Siemens Energy. Archimede is combining the advantages of a 5 MW solar field with a 750 MW combined cycle. The solar field, that consists of 30,000 m^2 of reflective area, uses molten salt (60% $NaNO_3$ and 40% KNO_3) as HTF. The use of salt-HTF allows higher operating temperatures of about 550 °C. The molten salt is then stored in a hot tank and is used to generate steam to power a Rankine cycle. This configuration reduces the consumption of fossil fuels so that carbon dioxide emissions is reduced by about 7300 t.

2.2. Under construction ISCCSs

2.2.1. Agua Prieta II [37]

The Agua Prieta II is being constructed close to the city of the Agua Prieta in the state of Sonora, Mexico. This ISCCS has been promoted by the Mexican Federal Electricity Commission (CFE) and supported by the Global Environment Facility (GEF) of the United Nations' Development Program. It is intended to have an output of approximately 465 MW with a 12 MW contribution from the solar field. The project will be developed by a consortium made up of the Spanish firms Elecnor and Sener. It has been planned to be commissioned in April 2013. The customer of the ISCCS electricity produced is the Mexican state power provider Comisión Federal de Electricidad.

2.2.2. Ningxia [28,31]

The Ningxia ISCCS is situated in Yinchuan, Ningxia, China, at northern latitude of 38° 31′ 54.48″ and a western longitude of 106° 13′ 26.4″ and at an elevation of 923 m. More details about the project are reported in Table 3. The project is owned by Hanas New Energy Group. The construction has been started in October 2011 and it has been planned to come online in October 2013.

2.3. Planned ISCCSs

2.3.1. Palmdale [38,39]

The Palmdale plant is planned to be located south of East Avenue M (E Ave. M) in the northernmost areas of the City of Palmdale in California, US. The plant will have a nominal electrical output of 617 MW. The solar field is intended to deliver about 10% of the total generated electricity during sunny periods. The project is going to be developed by Inland Energy, Inc. The Palmdale ISCCS plant would comprise two natural gas-fired gas turbines of 155 MW each, two heat recovery steam generators, 260 MW steam turbine and 250 acre-parabolic trough solar field.

2.3.2. Victorville 2 [40]

The Victorville 2 (VV2) will be implanted at the Southern California Logistics Airport (SCLA – formerly, George AFB). The plant would have a net electrical output of 563 MW. The Palmdale project developer will also manage the development of VV2. The VV2 is intended to combine two 154 MW gas turbines, two HRSGs, a 268 MW steam turbine and 250 acre-parabolic trough solar field. The solar field would generate up to 50 MW but with plant auxiliary loads of about 13 MW.

2.3.3. Abdaliya [41,42]

The Abdaliya ISCCS will be developed in Kuwait with a total capacity of 280 MW. The solar electricity would be about of 60 MW. In this context the solar fraction is around 22% which represents an important ratio when compared with those of current integrated solar combined cycle systems. The plant is intended to be operated in fuel saving mode. Therefore, there will be a maximum in environmental benefit; including 48,000 t of CO_2 less emission than pure fossil fuels combined cycle of similar capacity. The Abdaliya project is currently under development and will soon become the pioneer in solar thermal power plant in Kuwait. Table 4 provides more design data of the ISCCSs that are in the planning stage.

Table 3
Design data of underway ISCCS [31,36].

Project/plant name	Company/owner	Technology	Country	Location	Capacity (MW)	Solar fraction (MW)	Starting date	Coordinates	Break ground date
Agua Prieta II ISCC	Comision Federal de Electricidad	Parabolic trough-ISCC	Mexico	Sonora	478	14.00	June 2013	30° 17′ 43.8″N 111° 4′ 55.2″W	November 2011
Ningxia ISCC	Hanas New Energy Group	Parabolic trough-ISCC	China	Yinchuan, Ningxia	–	92.00	October 2013	38° 31′ 54.48″N 106° 13′ 26.4″E	October 2011

(–) Not available.

Table 4
Planned ISCCSs design data [31,36,38,40,43].

Project/plant name	Company/owner	Technology	Country	Location	Capacity (MW)	Solar fraction	Starting date	Land area (ha)
Palmdale Hybrid Power Plant	City of Palmdale	Natural gas-ISCC	The US	Palmdale, California	617	50.00	–	152
Victorville 2 Hybrid Power Plant	City of Victorville	Natural gas-ISCC	The US	Victorville, San Bernardino County, California	563	50.00	2013	388
Abdaliya	–	Natural gas-ISCC	Kuwait	–	280	60.00	–	–

(–) Not available.

3. Parabolic trough technologies applied in the ISCCS

In solar thermal power plants the collectors are usually used to generate steam to power a thermodynamic cycle. The steam can be generated directly into the absorber tube. This technique is called Direct Steam Generation (DSG). Another technique is the use of a Heat Transfer Fluid (HTF) to transport solar thermal energy from the collectors to a heat exchanger where steam is generated. This section provides the basic of these two concepts and a short comparison between them.

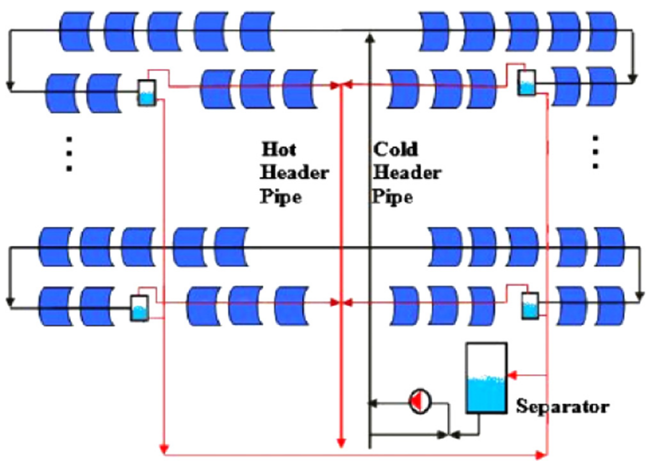

Fig. 1. Typical DSG-ISCCS solar field layout [44].

3.1. *Direct Steam Generation (DSG) Technology [44]*

In the Direct Steam Generation (DSG) concept steam is, as shown in Fig. 1, generated directly in the absorber-tubes of the parabolic trough collectors. This concept has been successively developed and tested in various R&D projects. The most important R&D projects are highlighted in Table 5. There are three basic DSG processes, namely once-through, injection and recirculation. Each process requires solar field composed of long rows of PTCs connected in series to perform the complete DSG process, i.e., water preheating, evaporation and steam superheating. In the once-through process, all the feed water is introduced at the collector row inlets and converted into superheated steam as it circulates through the collector rows. In the injection process, small fractions of feed water are injected along the collector row. The third option, the so-called recirculation process, a water steam separator is placed at the end of the evaporating section of the collector row. A comparison between the three processes is illustrated in Table 6.

3.2. *Heat Transfer Fluid (HTF) technology [44–47]*

The HTF technology has been commercially introduced in 1984. In such a concept, the reflective area of the solar field collects the

Table 5
Recent R&D activities in DSG concept [47].

R&D Project	Period	Partners	Objectives
GUDE	1993–1996	DLR, Siemens, TUM, ZSW	Thermo-hydraulic effects in horizontal receiver tubes
PRODISS/ ARDISS	1996–1999	DLR	Modeling, simulation and control of a collector loop
DISS I/II	1996–2002	CIEMAT, DLR, Flagsol, Iberdrola, ZSW, Siemens/KWU	Investigation of the thermo-hydraulic aspects of DSG under real solar conditions Test of three basic DSG processes, i.e., once-through, injection, and recirculation Technical feasibility of the DSG process Development and validation of simulation tools
INDITEP	2002–2005	CIEMAT, DLR, Flagsol, Iberdrola, Siemens, ZSW	Optimization of DSG components including separator, ball-joints, receiver. The detailed design of a first pre-commercial DSG plant
SOLDI	2004–2006	DLR, (Siemens)	Evaluation of separation concepts Process heat generation Dynamic model library
DISSTOR	2004–2007	DLR, Züblin, SGL Carbon, CIEMAT, Iberdrola, Flagsol,CNRS, Solucar	Development, erection and operation of a latent heat storage system
DIVA	2005–2007	SCHOTT, DLR, (Flagsol, KK&K)	Receiver development for 500 °C Detailed system analysis
ITES	2006–2009	DLR, Züblin, Siemens	Planning, erection and operation of a integrated storage system Optimized control strategies
FRESDEMO	2006–2008	MAN, SPG, (DLR, FhG-ISE, PSE)	Planning, erection and operation of a Fresnel collector with DSG Qualification of the collector
DETOP	2009–2010	Solar Millennium, Flagsol, DLR, Schott Solar, Züblin	Preparation of a demo plant Detailed system analysis
FRESDEMO 2	2009–2013	Schott Solar, DLR, Novatec Solar, FhG-ISE	Optimization of Linear Fresnel Technology and operation
DUKE	2011–2014	DLR, Solarlite, (CIEMAT)	Extension of DISS plant to1000 m Demonstration of once- through operation

DNI into the absorber-tubes where it is converted into thermal energy; leading to an increase in the temperature of the HTF circulating through the solar field. The HTF transfers the solar thermal energy through the so called Heat Solar Steam Generator HSSG to the power conversion system. Indeed, the HSSG is the link between the solar field and the power conversion system. It is a heat exchanger where the solar heat is used to generate steam to power the thermodynamic cycle. The HTFs could be non-freezing hydrocarbon, silicone oil or Molten Salt. The use of HTF overcomes the disadvantages associated with the DSG concept in particular high vapor pressure and risk of freezing. Nevertheless, HTFs such as oil can result in some problems such as fire when leaking out from the absorber-tubes or piping. Besides that, they are expensive. They are also extremely viscous at low temperature, a situation that requires additional power for pumping during nonsunny periods. Higher pressure drop and additional O&M costs of the HTF related equipments are other disadvantages of the HTF technology.

3.3. Comparison between the Direct Steam Generation and the Heat Transfer Fluid (DSG vs. HTF) [44]

As it is illustrated in Table 7, the DSG technology is more promising than the HTF technology since it does not require a HSSG and the power needed for the circulating pump is significantly reduced (lower parasitic). The implantation of DSG technology in the ISCCSs would bring many benefits because it leads to an increase in the operation temperature of the Rankine cycle (above 400 °C) and a reduction in the investment costs. Nevertheless, the DSG concept faces important challenges due to the two-phase flow which induces some problems related to solar field control, process stability, stress in the receiver pipes and higher steam loss.

In the DSG, the HTFs which include oils and molten salt in addition of some gases, would be no longer necessary and temperature limitation and environmental risks associated with the HTF would be avoided.

4. A review of studies and recent R&D activities

Recent studies have already pointed out that about a half of the cost reduction potential for CSP technologies can be attributed to R&D activities [4,12]. In this section, we have reviewed the most important findings of the previous R&D activities on the ISCCS. The presented methodology could be very helpful in identifying future R&D priorities.

4.1. Natural gas-ISCCS

Natural gas is the cleanest non-renewable resource that is originally obtained from the sun. Actually, power generation using natural gas is a healthy 21% and it is still on the increase. The present section focuses on the concept that combines solar energy and natural gas. This concept permits not only a sizable reduction in environment degradation but could also be considered as an intermediate step before the all solar power generation.

Table 6
Comparison of the three DSG processes [44].

Process	Once-through	Injection	Recirculation
Costs	Lowest	High	Higher
Complexity	Simple	More complex	Complex
Performance	Best	Better	Better
Controllability	Worse	Better	Better
Flow stability	Worse	Good	Better
Investments	Lower	High	Higher
Parasitic	Lower	High	Higher

Table 7
Comparison between DSG and HTF technologies [47].

	DSG technology	HTF technology
Heat exchangers	No	Yes
Operating temperatures	Promising	Limited
Efficiency	Higher, promising	Medium, limited
Fluid toxicity	No	Yes
Configuration	Complex	Simple
Phase flow	Two phase	One phase
Control effort	Higher	Lower
Thermal storage [78]	Expensive, demonstrative stage	Less expensive, commercial
Temperature gradients	Higher	High
Technology stage	Demonstrative	Commercial
Scaling up [78]	With additional costs	Easier
Performance enhancement	Promising	Limited
Environmental risks [78]	Low	High
O&M costs [78]	Lower	Higher
Process stability [78]	Less stable	Stable
Leaks [78]	Higher	Low
Solar field size	Smaller	Large
Advancements	**Very promise**	**Limited**

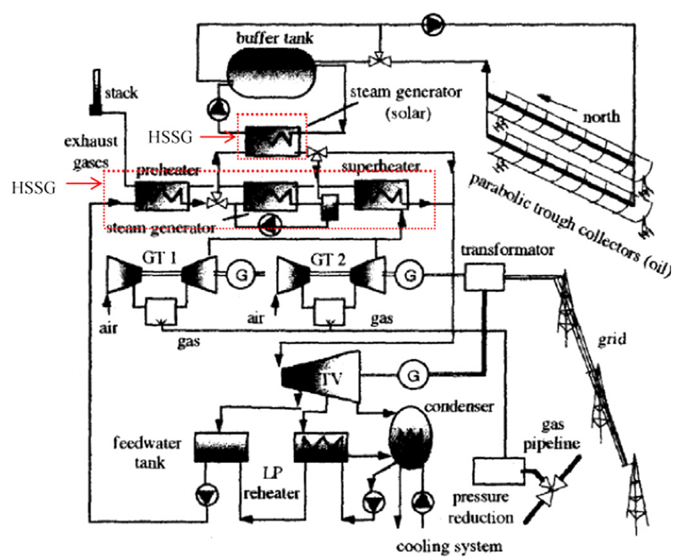

Fig. 2. First proposed HTF-ISCCS configuration [48]. The solar field feeds hot oil to a buffer tank that is linked to the HSSG which is itself linked to the HRSG.

4.1.1. HTF-ISCCS

Within the framework of the PAESI, which stands for “Project d'Aménagement Energétique Solaire Intégré”, Allani et al. [48] have studied the technical and economic feasibility of implanting HTF-ISCCS in Tunisia. The proposed configuration, illustrated in Fig. 2, has been designed to deliver about 88 MW of electricity during sunny periods, while produce 58 MW at night when operating in a combined cycle mode. The combined cycle is made up of two gas turbines and an oversized steam turbine. The solar field consists of parabolic trough collectors that feed hot oil to both a buffer tank and a Heat Solar Steam Generator (HSSG) which is

itself linked to the Heat Recovery Steam Generator (HRSG). The authors have examined two operation strategies, in terms of thermal performance, Greenhouse gas emissions and economic aspect. These two strategies are the maximum efficiency strategy and the maximum power strategy. They have found that the maximum power strategy offers higher potential for CO_2 mitigation than the maximum efficiency and the more economic plant corresponds to smaller solar field. They also have reported that the ISCCS is more advantageous than Solar Electric Generating System (SEGS).

For enhancing the HRSG and the HSSG, Kane and Favrat [49] have coupled a pinch technology approach with a thermodynamic modeling to optimize mass flows and pressure levels of steam cycle. They have found that the exergy losses in the heat exchangers network are strongly dependent on the solar thermal energy input from the solar field. Hence, they have proposed the use of higher pressure steam cycle to improve exergy efficiency.

Again and in order to optimize the heat exchangers network, Kane and Favrat [50] have examined the effect of the pressure level and the flow interaction between the HRSG and HSSG on the energy efficiency of the HTF-ISCCS. They have considered three cases of pressure levels, i.e., simple pressure level for both HRSG and HSSG, double pressure levels for HRSG while simple pressure for HSSG and double pressure levels for both heat recoveries. For each case, various layouts of steam interactions between the HRSG and the HSSG have been examined. The results have shown that an ISCCS with double pressure levels, as shown in Fig. 3, is the best configuration for the (PAESI) power plant because of the higher thermal efficiency.

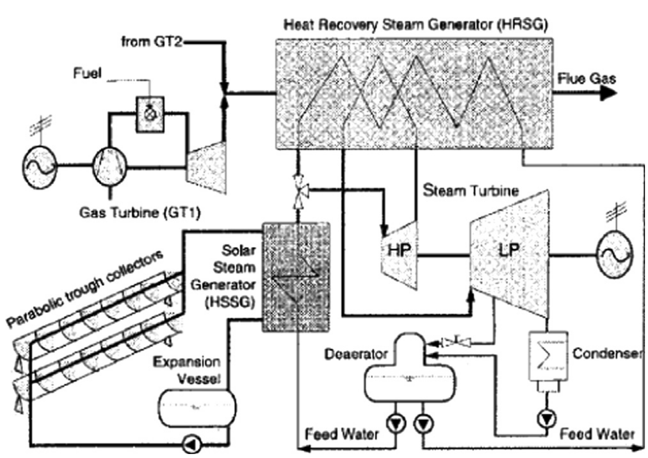

Fig. 3. Other HTF-ISCCS design [49]. Unlike Allani et al. [48] design, the buffer tank is removed in the recent design to reduce losses and therefore improving thermal performance.

In the previous studies, Kane et al. [48–50] have found that if the steam turbine is on the off design conditions, the minimum pinch cannot be kept and the exergy losses are going to be strongly dependent on the amount of the thermal energy input from the solar field. For solving this issue, they have coupled a pinch technology approach with a mathematical programming optimization algorithm to maximize the exergy efficiency in the steam generators (HRSG, HSSG) with regards to the steam turbine operation conditions [51]. The authors have investigated the performance of the ISCCS for different steam turbine configurations and for different operating modes. The results have shown that a power plant with double pressure-reheat and smaller solar field provides better performance. Moreover, it could be competitive to conventional CC power plants if a decisive subsidy and CO_2 taxes come to pass.

To investigate the performance of HTF-ISCCS under the Iranian climate, Hosseini et al. [52] have technically and economically compared six thermal power plants considering various configurations and capacities, i.e., ISCCS with 67 MW solar field, ISCCS with 67 MW solar field and fuel back-up, ISCCS with 33 MW solar field, ISCCS with 33 MW solar field and fuel back-up, SEGS and a simple gas turbine (GT). They have concluded that the ISCCS with 67 MWe solar field is the most suitable configuration for the first solar power plant in Iran. Such a power plant is capable of saving about 59 million $ in fuel consumption and reducing about 2.4 million tons in CO_2 emissions during the 30 years of operation. Additionally taking into account the environmental costs, its Levelized Energy Cost (LEC) is respectively 10% and 33% lower than that of a CC and a GT. Fig. 4 represents the ISCCS configuration proposed by Hosseini et al.

Baghernejad and Yaghoubi [53] have performed the energy and exergy analysis on the ISCCS located in Yazd, Iran. ISCCS configuration

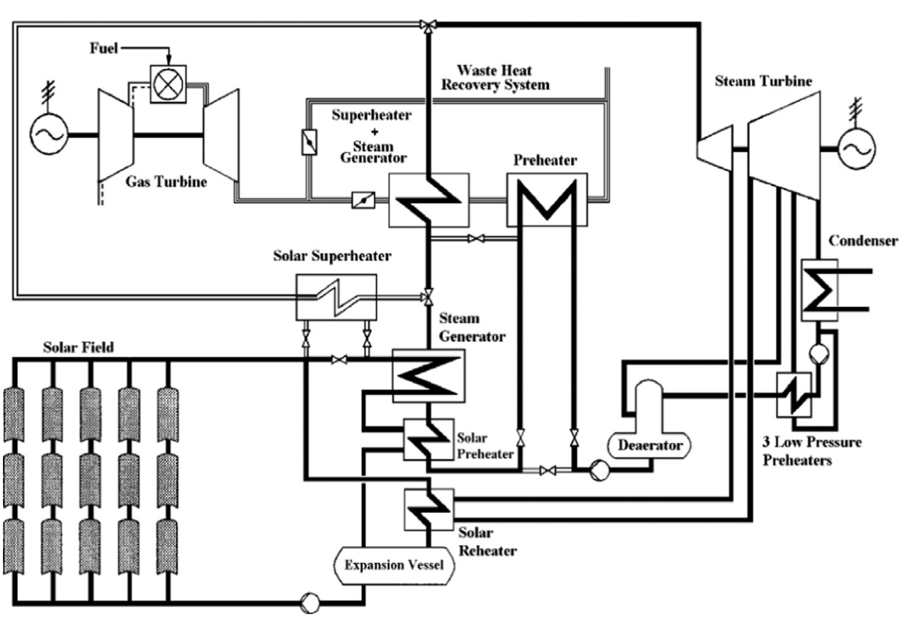

Fig. 4. Suggested HTF-ISCCS by Hosseini et al. [52]. Solar thermal energy is used for preheating water, generating steam, superheating and reheating.

is shown in Fig. 5. They have estimated the energy and exergy losses to assess the performance of the power plant, including the energy and exergy efficiencies of the key components. They have found that the combustor of the gas turbine is the major part of exergy losses with 29.62% followed by the solar field (9%), while major energy losses take place in the condenser and the stack. The analysis has also indicated that the solar field is the least efficient component in the ISCCS because its exergy efficiency does not exceed 27%. Nevertheless, the energy and exergy efficiencies for the overall ISCCS have been found to be respectively around 46.17% and 45.6%. These values are higher than those of the SEGS and even higher than some fossil power plants.

Baghernejad and Yaghoubi [54] have coupled the exergoeconomic principles and genetic algorithms to optimize the ISCCS of Yazd, in terms of the investment cost, the exergy destruction cost and the electricity cost. In order to do so, the authors have developed a code using MATLAB software and they have validated it with the obtained results of classical mathematical optimization approach published by Silveira [55]. The simulated results have confirmed the exergy analysis of Baghernejad [54] and have shown that the exergy efficiency of the ISCCS could be improved from 43.79% to 46.8% while the exergy destruction cost reduced by 14.82%. Moreover, the LEC of the steam turbine and the gas turbine could be decreased by around 7.1% and 1.17% respectively, but with 13.3% increase in capital investment. In other words, the longer are the operation duration of the solar field and of the lifetime of the power plant, the lower is the LEC.

Baghernejad and Yaghoubi [56] have focused on the energy and exergy analysis of Yazd ISCCS. They have used three balance equations, i.e., mass, energy and exergy balance equations to locate the irreversibility and energy and exergy losses of each component of the plant. The exergy analysis has indicated higher exergy losses in the combustor followed by the solar field and the gas turbine exhaust which correspond respectively to 29.62%, 9%, and 7.78% of the total exergy input into the plant. On the other hand, the energy analysis has revealed that the major energy losses take place at the condenser and stacks which correspond respectively to 35.94% and 10.15% of the total energy input. In this context, the overall energy and exergy efficiencies of the ISCCS have been found to be respectively 46.17% and 45.6%. The authors have also identified the source of the previous losses so that future studies could be focused on the enhancement of the ISCCS performance.

For Hassi R'Mel ISCCS, Khaldi [57] has carried out the energy and exergy analysis of the first HTF-ISCCS in Algeria, considering the design point conditions. He has used the Cycle-Tempo program developed by the Delft University of Technology for assessing the energy and exergy efficiencies of the power plant, and therefore, locating the inefficient components. For the heat exchangers he has used the exergy flow diagram together with the value diagram in order to provide more in-depth analysis. The simulation study has been revealed that the combustor of the gas turbine and the solar field are the major sources of the energy and exergy losses, whereas, the turbo machineries including compressor and

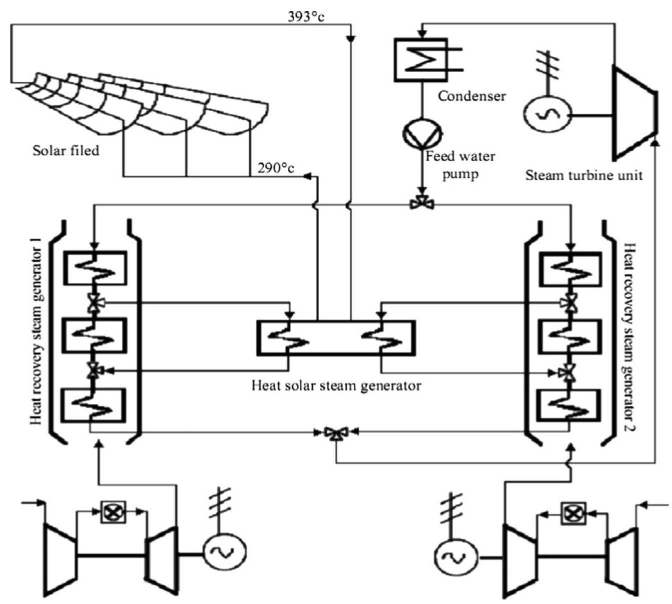

Fig. 6. HTF-ISCCS with simple pressure level [59]. The most preferred method for converting solar energy into electric power has been applied.

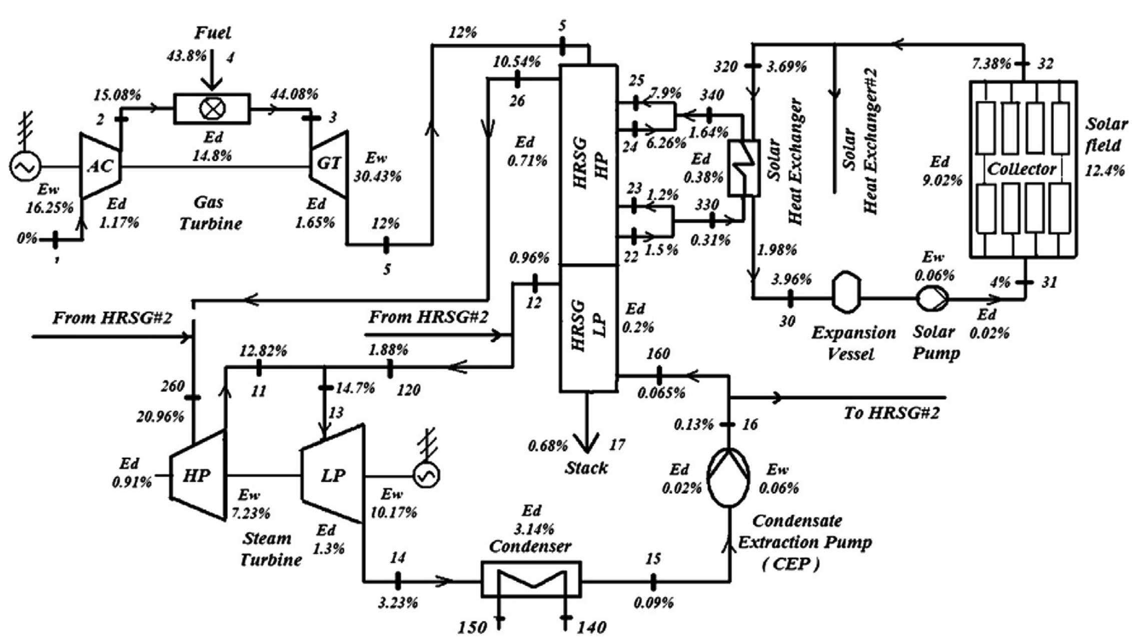

Fig. 5. Yazd HTF-ISCCS design, solar energy is used to generate steam [53].

turbines offer higher performance. The author has also presented many information about the design data of Hassi R'Mel ISCCS and he has found that the solar energy share is about 14% (which correspond to 22 MW), while the solar exergy share is 12% (18.4 MW). At the design point, the energy and the exergy efficiencies of the power plant have been respectively 56% and 53%.

Derbal-Mokrane et al. [58] have used the TRaNsient SYstems Simulation (TRNSYS) software to simulate the annual performance of Hassi R'Mel HTF-ISCCS. The library of Solar Thermal Electric Component (STEC) models has been used for both solar field and conventional combined cycle. The results have shown that the power plant can produce 150 MW with 52% efficiency. The solar fraction has been found about 30 MW of the total power plant output.

Behar et al. [59,60] have developed a mathematical program to investigate the performance of Hassi R'Mel ISCCS, using visual FORTRAN. They have proposed, as shown in Fig. 6, a HTF-ISCCS with simple pressure level whereby the most preferred method for converting solar energy into electricity has been selected. The proposed power plant has been made up of 2×47 gas turbines, an oversized steam turbine of 80 MW maximum capacity and a solar field of 183,120 m^2 reflective area. It has been observed that the output from and the efficiency of the power plant response sensibly to solar thermal energy input, and the more the solar energy the better the performance. At the design point, the electricity production and the efficiency of the HTF-ISCCS have been found to be better than those of the combined cycle power plant (134 MW, 57.5%) by 17% and 16.5%, which are correspond to 157 MW and 67%, respectively.

For Lybia, Elhaj et al. [61] have developed a mathematical model, in Visual Basic 6.0, to predict the benefits of modifying an existed gas turbine, located in Misurata city, into a HTF-ISCCS. The meteorological data of the city have been taken from Desalsolar 1.0 software database while the properties of the steam have been calculated using the Computer-Aided Thermodynamics software (CATT2). They have analyzed the effect of solar concentration ratio and the effectiveness of the HSSG on the performance of the proposed integrated solar combined cycle system. It has been reported that the modification of a simple Brayton cycle into an ISCCS offers many advantages in terms of electricity production and thermal efficiency.

Again, Elhaj et al. [62] have investigated the impact of the solar field, the gas turbine and the steam turbine on the performance of a HTF-ISCCS. They have focused on the effect of the efficiency, the solar contribution and the main design data of these major components featuring the power plant. The simulation results have revealed that the factor affecting the performance of the plant most is the ratio of the steam mass flow to that of the HTF. The performance analysis has also shown that solar field, steam turbine and gas turbine efficiencies can achieve respectively 62%, 32% and 40%. Therefore the value of overall plant efficiency can reach 29%.

Once more, Elhaj et al. [63] have considered the exergy analysis of a HTF-ISCCS. The HTF-SF has been supposed to consist of several 3 m^2 parabolic trough collectors, while the CC power plant have been made up of single gas turbine and a Rankine cycle of 80% isentropic efficiency. The authors have carried out sensitivity studies including the effect of solar radiation, ambient temperature and compressor pressure ratio on the exergy efficiency of each components of the power plant. They have found that the higher is the compression ratio the larger is the exergy efficiency. Nevertheless, it has been observed that the combustor of the gas turbine and the solar field are the main sources of exergy losses with 39% of the fossil fuel input for the former and 33% of the DNI for the solar field.

For Europe, Bakos and Parsa [64] have focused on the economic analysis of HTF-ISCCS and investigated the effect of solar field size on the costs of the power plant in Southern Greece. The selected ISCCS in this study is made up of 35 MW gas turbine, a 15 MW steam turbine and a parabolic trough solar field. The solar field is supposed to be in the range from 30,000 m^2 up to 180,000 m^2 whereby six fields with different sizes have been considered. The TRNSYS-STEC software has been used to model and simulate the hourly fuel consumption and solar contribution in two operation modes, i.e., fuel saving and boosting modes. The results have been revealed that fuel saving mode can provide lower LEC than boosting mode. Furthermore, the larger the solar field the higher the cost of electricity production. The authors have concluded that, if exported electricity price, in Greece, rises from 0.05026 €/kWh to 0.060 €/kWh, the ISCCS will become cost-effective even with larger solar field.

Franchini et al. [65] have compared the thermal performance of HTF-ISCCS with a parabolic trough technology to that with a Central Receiver technology under Sevilla climate (Spain). In order to do so, they have coupled TRANSYS-STEC with Thermoflex software to analyze the effect of CSP technology on the thermal performance of the ISCCS. The hourly simulation has shown that during summer the ISCCS with parabolic trough technology can offer better performance than the one with tower technology due to higher solar field optical efficiency, i.e., the parabolic trough solar field collects more solar radiation than heliostats field with thermal efficiency up to 60% in warm days. Nevertheless, the annual performance simulation has been indicated that ISCCS with tower power technology produces more electricity with higher efficiency than ISCCS with parabolic trough. An important finding is that, with the exception of the hot summer months, the central receiver technology provides a yearly much higher stable energy collection than the parabolic trough one. It must be noted that stable solar input in the thermodynamic cycle maintains higher performance and eliminates the additional costs induced by the variation of solar radiation. The selected ISCCS design is illustrated in Fig. 7.

For India, Siva Reddy et al. [66] have presented a short review of studies on solar thermal power plants including parabolic trough, central receiver and dish sterling power plants. The ISCCS has been slightly highlighted. The review includes an economic assessment of the CSP-plants under the Indian tropical climate. It has been shown that for 50 MW CSP-plant, the dish sterling technology offers lower LEC than the other two solar technologies considering a 30 years lifespan and a 10% interest rate on investment.

For Morocco and Egypt, Brakmann [67] has presented the status and the basic design data of both Beni Mathar and Kuraymat ISCCSs. He has also presented the performance of the latter as a function of ambient temperature and solar radiation intensity for three operating modes, i.e., (1) power boosting mode which requires an oversized steam turbine and thus results in higher cost and larger part load losses, (2) gas turbine throttling mode when solar radiation is higher and thus resulting in less exhaust heat to the HRSG, and (3) excess solar heat dumping mode by defocusing some collectors and thus allowing the operation of both the gas turbine and the steam turbine at full load.

Brakmann et al. [68] have reported the technical data of Beni Mathar ISCCS. The design concept, the geographical location of the site, the site index map, the topographic map and the power plant layout have been briefly outlined. They have also presented a summary of technical parameters of the power plant.

Brakmann et al. [69] have reported the design data and the construction progress of Kuraymat ISCCS including the solar field and the combined cycle power plant. Kuraymat ISCCS plant configuration is shown in Fig. 8. For the solar field, they have described the construction process. For the combined cycle, they

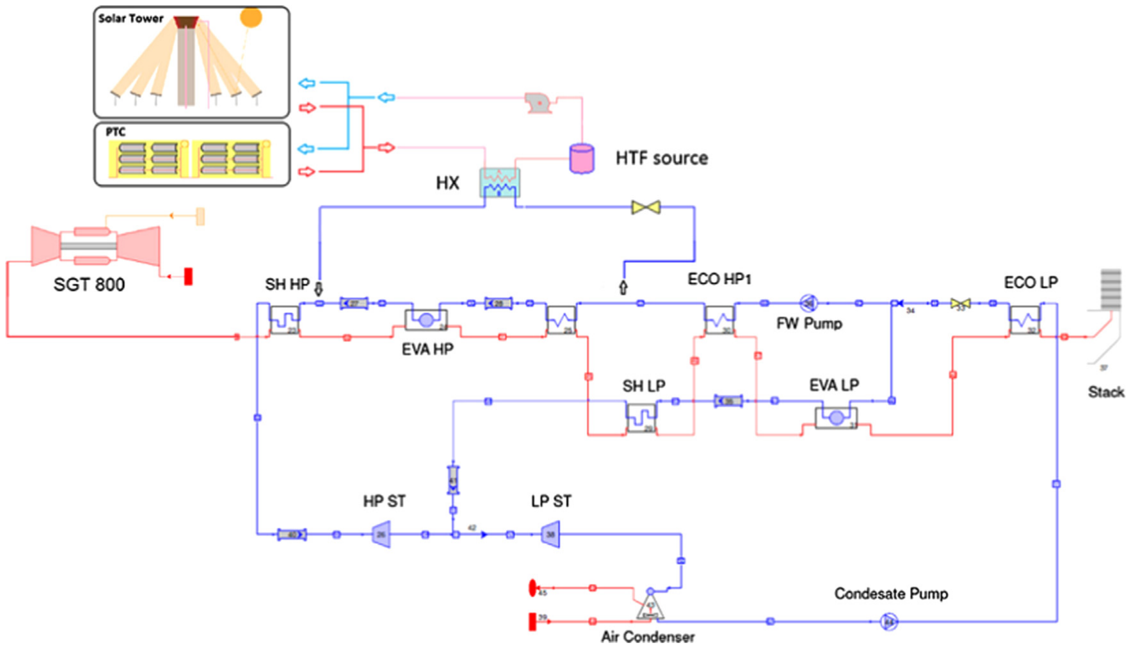

Fig. 7. HTF-ISCCS configurations by Franchini et al [65]. During summer days the ISCCS with a parabolic trough technology offers better performance than that with a central receiver system.

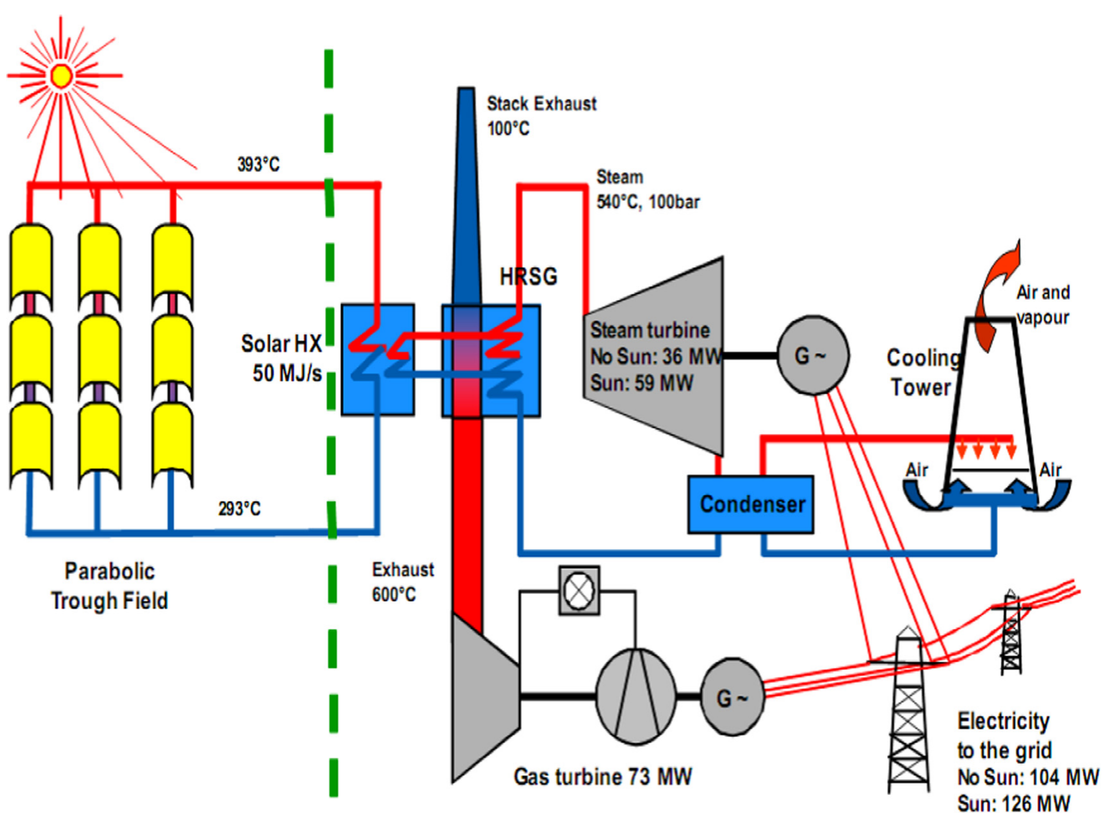

Fig. 8. Kuraymat ISCCS design [69].

have highlighted the construction works progress of the gas turbine unit, the HRSG, the HSSG, the steam turbine, the cooling system and the electric power system. The report includes important technical information.

For the US, Antoñanzas-Torres et al. [70] have investigated the impact of DNI, the solar field size and ambient temperature on the performance of the HTF-ISCCS operating in power boosting mode. In order to do so, they have selected two locations, i.e., Las Vegas (US) with higher DNI and Ciudad Real (Spain) characterized by lower DNI. The meteorological conditions of each site have been defined by their TMYs using Meteonorm which provides a year of hourly values of DNI, wind speed and air temperature. The

combined cycle has been made up of 270 MWe gas turbine and a 130 MWe steam turbine. The simulation using a new model implanted in the SAM software has shown better performance of the ISCCS during warm days, when solar radiation is higher. Moreover, the more the solar radiation the better is the performance compared to those of CC power plant. In other word, the CC power plant in Las Vegas has lower performance than the one in Ciudad Real, due to the higher temperatures, whereas the ISCCS offers better performance in Las Vegas than in Ciudad Real because of the higher DNI.

Turchi and Ma [71] have compared the performance of HTF-ISCCS with and without TES to those of SEGS. As shown in Fig. 9, in the proposed ISCCS, the gas turbine exhaust is used to heat the HTF in the ISCCS without storage whereas it is used to heat up the salt-HTF in the one with TES. The IPSEpro process software has been applied to simulate the ISCCS while SAM has been used to simulate the SEGS and a code implanted in Excel to simulate the gas turbine performance. The results have shown that the cost of electricity production is the lowest in ISCCS without storage followed by the one with storage, under US climate. It has also been found that the solar fraction in the novel integration scheme can far exceed any other ISCCS configurations and reach up to 64%. The authors have reported that the so called co-locate gas turbine/solar thermal hybrid designs introduced in this study avoids poor gas utilization efficiency and limited solar contribution associated with the implantation of widely operating ISCCS design. However, it has been observed that the thermal efficiency of the proposed design is about 48%, far less than that of previous design which can reach the limit of 68%.

Dersch et al. [72] have made a comparative study between the ISCCS, the SEGS and the CC power plants for various configurations. They have investigated the effect of the DNI, the solar field area, the Thermal Energy Storage (TES) and the operation mode on the performance of 50 MW triple pressure-reheat power plants. The analysis has been performed using the commercial computer software, GateCycle and IPSEpro. The results have revealed that the ISCCS has the highest thermal efficiency compared with the others. More particularly, the ISCCS efficiency is so much higher

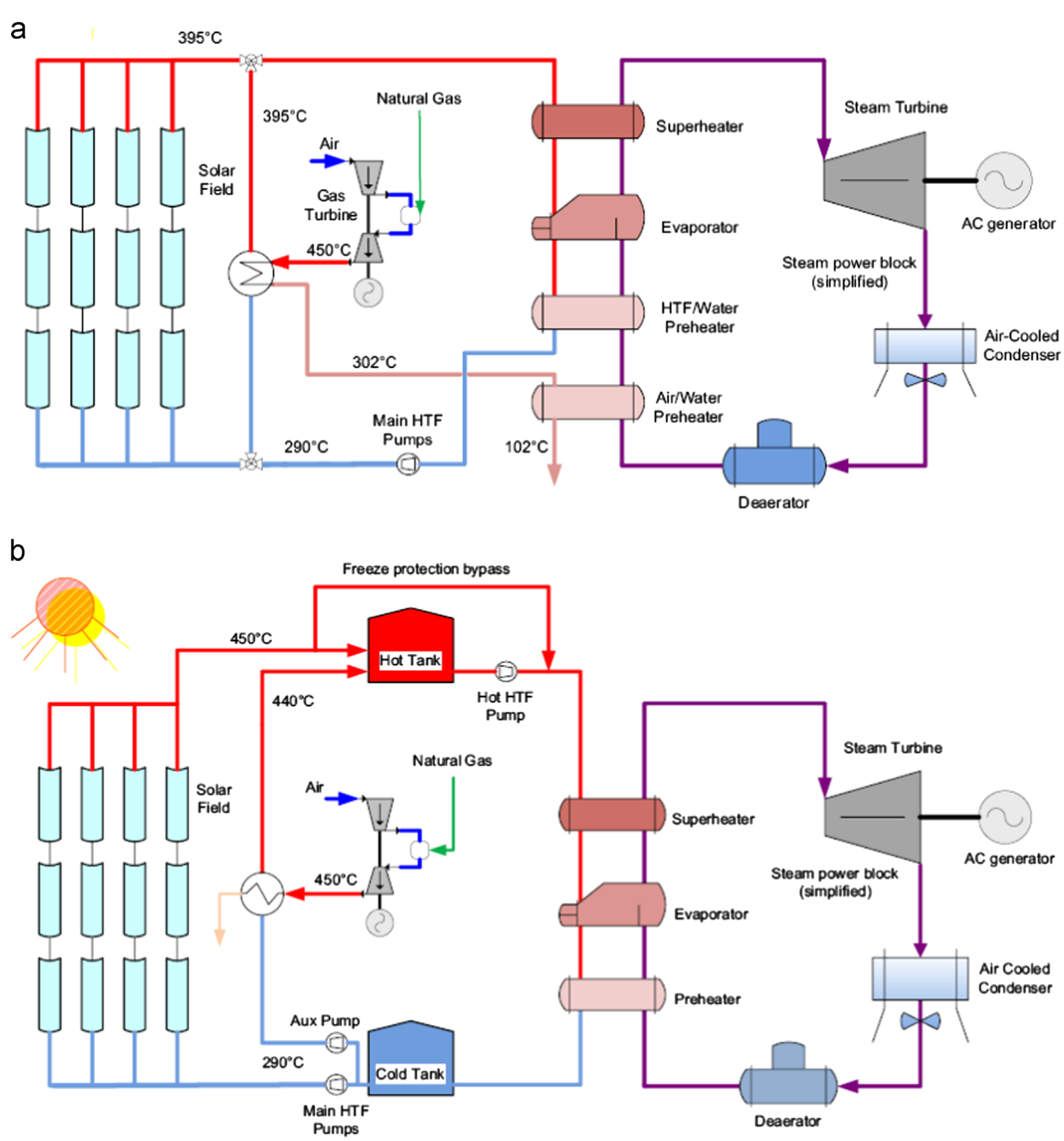

Fig. 9. HTF-ISCCS by Turchi and Ma [71]. The gas turbine exhaust is used to heat the HTF (a) whereas it is used to supplement the storage system (b).

than that of SEGS (68.6% for ISCCS vs. 34.7% for SEGS), while the SEGS offers lower GHG emissions, particularly in boosting mode. Other important results have also been reported; the solar Levelized Electricity Cost (LEC) is lower for the ISCCS in scheduled operation mode than in boosting mode. Besides, an ISCCS without TES has a 10–15% lower solar LEC than that with a storage system. The ISCCS that has been selected by Dersch et al. is shown in Fig. 10.

Siva Reddy et al. [73] have energetically and exegetically compared the performance of CC power plant to those of HTF-ISCCS with linear Fresnel solar field. In order to do so, the authors have developed a computational model using Engineering Equation Solver Software. The selected combined cycle has been assumed to be made up of two gas turbines, one multi-pressure heat recovery steam generator and an oversized steam turbine. They have also presented a detailed mathematical formulation of both the combined cycle and the solar field. The energy analysis of the CC has shown that there are major energy losses in the condenser followed by the HRSG, while major exergy losses take place in the combustion chamber followed by the HRSG. When compared to those of conventional combined cycle, the energetic and exergetic efficiencies of the HTF-ISCCS are both lower, i.e., 41.68% and 49.69% for CC vs. 53.93% and 54.47% for HTF-ISCCS, respectively.

Kelly et al. [74] have used GateCycle software to determine the optimal integrated plant configuration with three pressure levels. They have examined the effect of how solar energy is integrated into the power cycle and the effect of ambient temperature on the performance of the power plant, for different solar field sizes and heat recovery steam generators designs. The simulated results have indicated that the ISCCS design depends strongly on the solar field size. For instance, an annual solar contribution in the range of 1–2% can lead to a solar electricity efficiency of 40–42%. Nevertheless, the larger the solar field and thus the solar contribution, the lower is the efficiency. For example, increasing the solar contribution to 9% could reduce the net conversion efficiency to values in the range of 32–35%. Fig. 11 highlights the configuration considered by Kelly et al.

Gunasekaran et al. [75] have investigated four different configurations of HTF-ISCCS that are equipped with Carbon Capture and Storage (CCS) technology. The four integration schemes integrate solar energy in different ways, i.e., vaporization, preheating, heating of intermediate-pressure, and heating of low pressure steam of the Rankine cycle. The authors have used ASPEN CUSTOM to model the solar system while the power plant modeled by ASPEN PLUS and JACOBIAN. The results have indicated that the configuration that uses solar energy for evaporating or for heating intermediate-pressure water/steam offers higher electricity production than the other selected schemes. When compared with solar thermal power plants without CCS like solar hybrid gas turbine, it has been observed that the HTF-ISCCS-CCS with vaporization integration scheme is better than the most other solar hybrid systems in the literature.

Cau et al. [76] have introduced an advanced HTF-ISCCS concept that employs CO_2 as a heat transfer fluid. The proposed power plant, represented in Fig. 12, consists of 250 MW triple-pressure-reheated combined cycle and a parabolic trough solar field with an overall area of 120,960 m^2. They have used the GateCycle software for thermal performance and cost assessment. Since this software does not include CSP systems library, the authors have developed a new model for the solar field. Two processes for converting solar thermal energy into electricity are considered and compared. In case (1) solar energy has been used for preheating, evaporating and superheating water/steam, while in case (2) solar energy has been applied for generating steam. The thermal performance analysis has pointed out that the solar energy conversion efficiency is about 23–25% for a CO_2 maximum temperature of 550 °C while it decreases by about 1.5–2.0% for temperature of 450 °C,

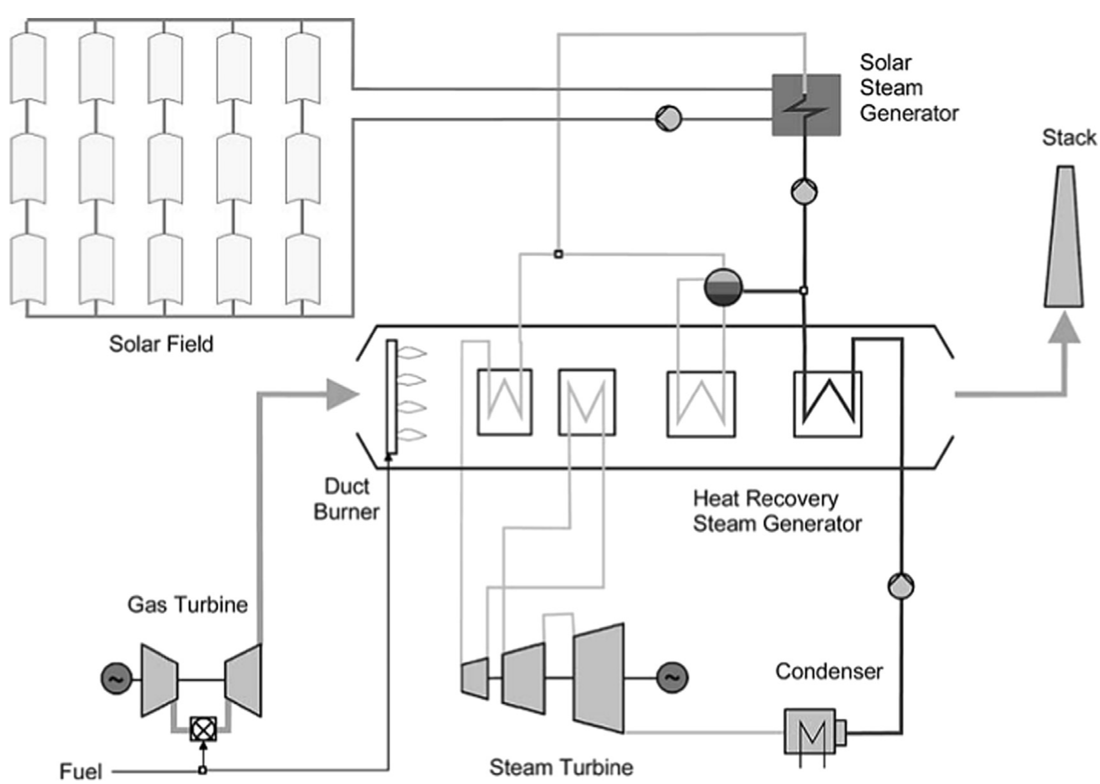

Fig. 10. HTF-ISCCS with single pressure level-reheat [72].

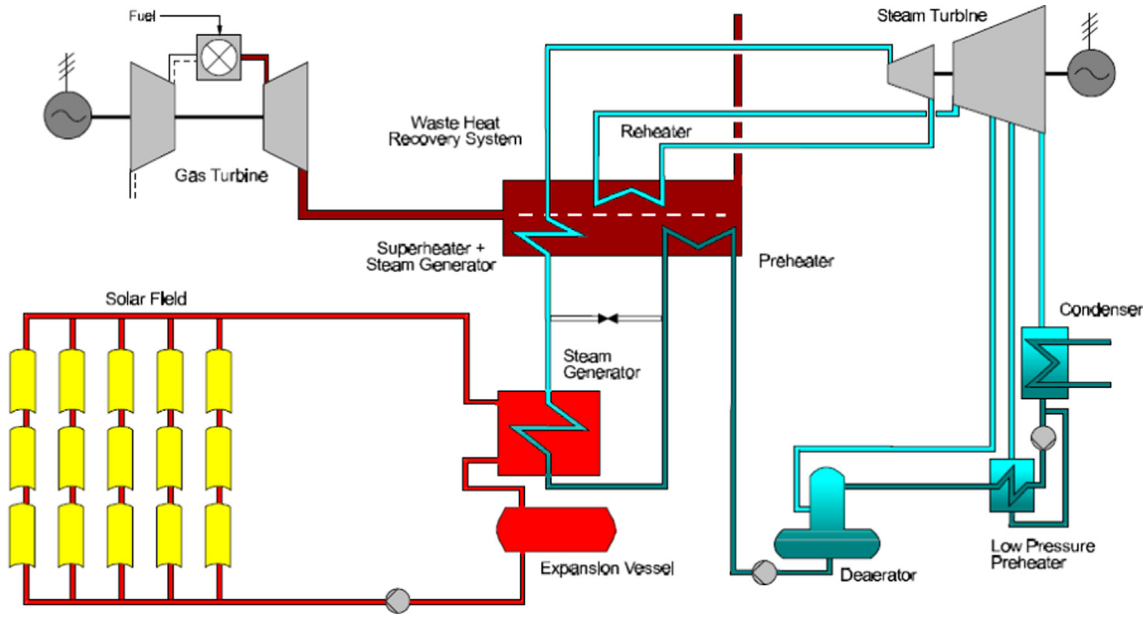

Fig. 11. HTF-ISCCS configuration studied by Kelly et al. [74].

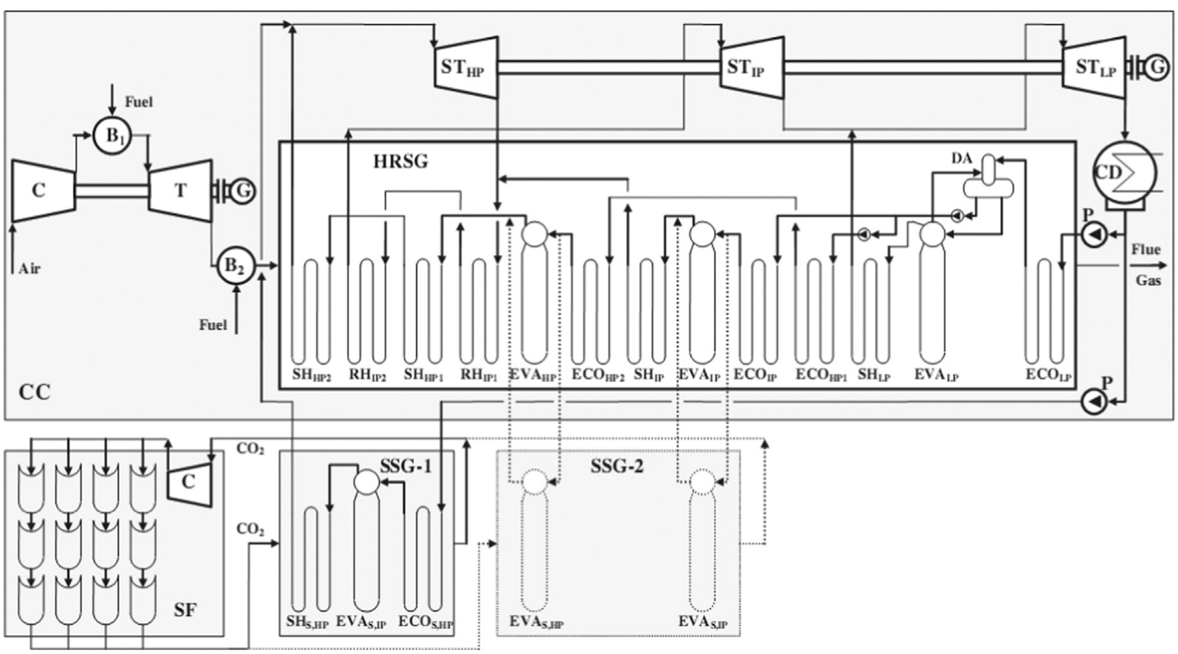

Fig. 12. Advanced configuration of CO_2-ISCCS by Cau et al. [76].

and the lower the temperature the lower the performance. This analysis has also revealed that the use of solar energy for producing steam (case 2) offers better performance than the case of preheating, evaporating and superheating water/steam. For instance, the increase in temperature from 450 °C to 550 °C improves the efficiency by 3.8% for the case 2 while enhances the efficiency by only 3.3% for the case 1. The main disadvantage of the proposed concept is the use of CO_2 as HTF since it requires 5–10% of the gross solar thermal power for compression process. The economic assessment have been shown that the capital cost of CO_2-ISCCS is about 50% higher than that of the CC plant, even though it leads to electricity increase of about 10%. When compared to that of CC power plant, the Levelized Electricity Cost (LEC) of the ISCCS has been found to be slightly higher (6.79 c€/kWh for CC vs. 6.91 c€/kWh for ISCCS). Furthermore the solar marginal LCE has been found to be about twice higher than that of CC, i.e., 13.77 c€/kWh for ISCCS with the case 1 and 13.48 c€/kWh for the case 2. The sensitivity analysis has revealed that the ISCCS with CO_2 as HTF would be competitive with CC power plant if the specific cost of the solar field decreases to 35 €/m^2, or, if the natural gas prices for a solar field reference cost of 220 €/m^2 reach 955 €/t.

Al-Sulaiman [77] has been interested in the exergy analysis of a novel HTF-ISCCS design shown in Fig. 13. The HTF-ISCCS plant consists of a parabolic trough solar field integrated with the steam and organic Rankine cycles. A mathematical code has been implanted in

Engineering Equation Solver (EES) to assess the exergetic performance including efficiency, exergy destruction rate, fuel depletion ratio, irreversibility ratio, and improvement potential. Seven working fluids for the bottoming cycle (organic cycle) have been tested and their performance compared: R134a, R152a, R290, R407c, R600, R600a, and ammonia. The exergy analysis has shown that the solar field is the main source of the exergy destruction and account for around 70% the total destructed exergy. This is followed by the evaporator which accounts for 19% of the total destructed exergy in the power plant. It has been deduced that the R134a working fluid is the most efficient since it demonstrates the best exergetic performance followed by R152a, whereas the R600a working fluid ranks the last with the lowest exergetic performance. The author has found that the proposed concept has an overall exergetic improvement potential of 75%.

4.1.2. DGS –ISCCS

For integrating the DSG technology into the Rankine cycle. Montes et al. [78] have investigated the performance of 220 MW DSG-ISCCS, for comparison to that of pure CC power plant, under two different climate types, i.e., Almeria (Spain), with a Mediterranean climate, and Las Vegas (US), with a hot and dry climate. The proposed DSG-ISCCS is represented schematically in Fig. 14. The simulation using the well-known software TRANSYS, has indicated that even though the CC power plant has lower performance in Las Vegas due to higher temperatures, the DSG-ISCCS offers better performance in Las Vegas than in Almeria, because of solar hybridization. Also, the global efficiency of the DSG-ISCCS in Las Vegas is better than in Almeria with 52.18% and 51.90% respectively. Furthermore, the economic analysis has revealed that the LEC of the power plant in the former location is lower than in the latter. More in-depth, the solar hybrid power plant has lower LEC than CC in Las Vegas (80.52 vs. 81.29 €/MWh), while it is higher than that of CC in Almeria with respectively 80.55 and 80.35 €/MWh.

Once more, Montes et al. [79] have investigated different solar hybridization sizes of 220 MW DSG-ISCCS for the Canary Islands, Spain. They have concluded that the larger the solar field the lower the performance of the steam turbine. For this reason, they have recommended a smaller solar hybridization that provides nominal operation during a year without significant overloads.

El-Sayed [80] has proposed the implementation of DSG-ISCCS at Kuraymat, Egypt. As shown in Fig. 15, the proposed power plant consisted of a 30 MW gas turbine, a 65 MW steam turbine and a solar field of 190, 000 m^2 which correspond to 90 MW of solar thermal energy at the design point of 720 W/m^2 solar irradiation. The analysis has been carried out in both fuel saving and power boosting modes. The author has investigated the cost benefit ratio of the ISCCS and found values between 1.25 and 1.35, depending on the operation mode. He has also concluded that power boosting is more economical than fuel saving mode. Furthermore, the sensitivity analysis has been pointed out that DSG-ISCCS could become economically feasible if the cost of solar field is reduced and the natural gas prices increases.

Elsaket [81] has developed a mathematical code for simulating the performance of DSG-ISCCS under Libyan climatic conditions. The study has focused on modifying the existing 4×51 MW Brayton cycles into an integrated solar combined cycle with a direct steam generation technology. The author has presented in details the mathematical formulation of each component as well as the flowcharts of the developed code. The results have shown an efficiency of about 78% for the solar field under Libyan climate. They have indicated that the idea of modifying existed gas turbine would offer many advantages. For instance, it increases the plant capacity to 286.12 MW at the design point which leads to saving about 151,260 t of fossil fuels annually, therefore, avoiding 468,910 t of carbon dioxide per year.

Li and Yang [82] have introduced and analyzed, under Yulin city in China, a two-stage solar input DSG-ISCCS. As shown in Fig. 16, the plant is made up of one gas turbine, dual pressure-single reheat HRSG and an oversized steam turbine. They have used the ASPEN PLUS process simulation software to optimize and evaluate the hourly, monthly and annual performance of the proposed

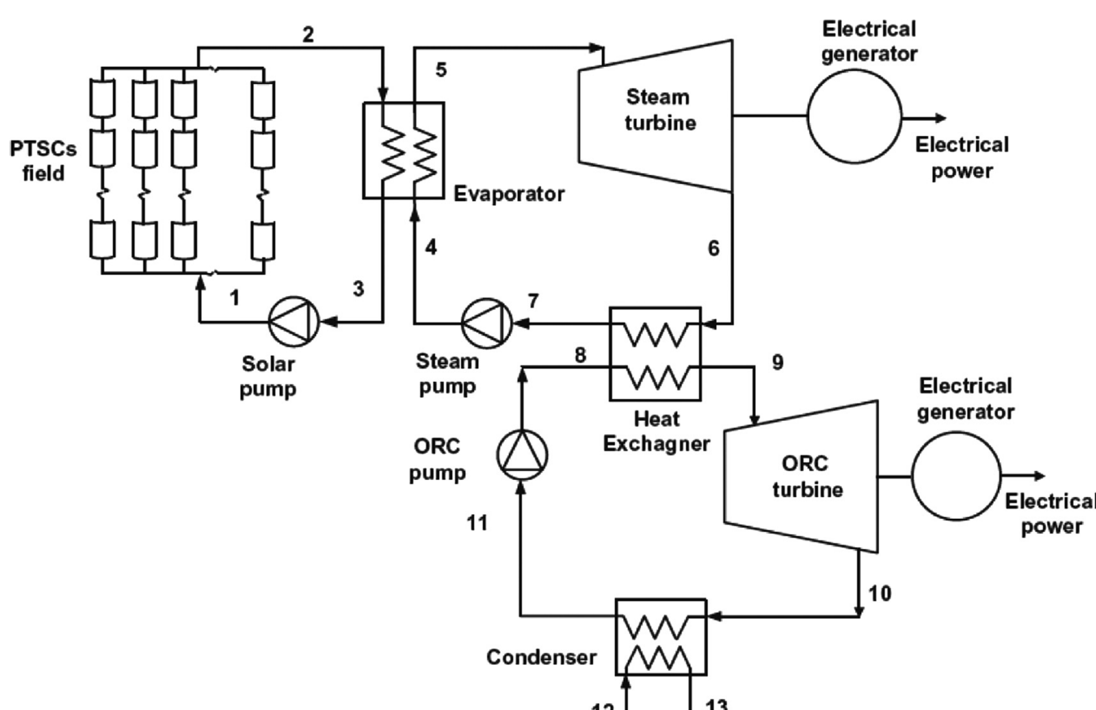

Fig. 13. Advanced HTF-ISCCS with Steam Rankine cycle (topping cycle) and an organic Rankine cycle (bottoming cycle) [77]. Such a concept allows improving exergy efficiency and producing electric power at lower temperatures.

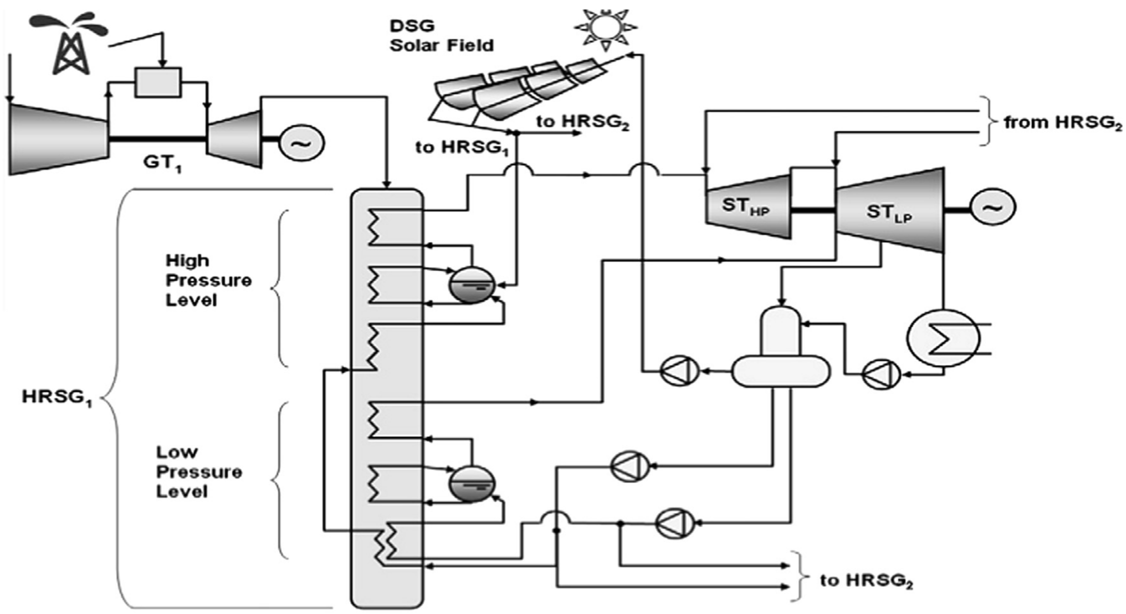

Fig. 14. DSG-ISCCS with double pressure level proposed by Montes et al. [78].

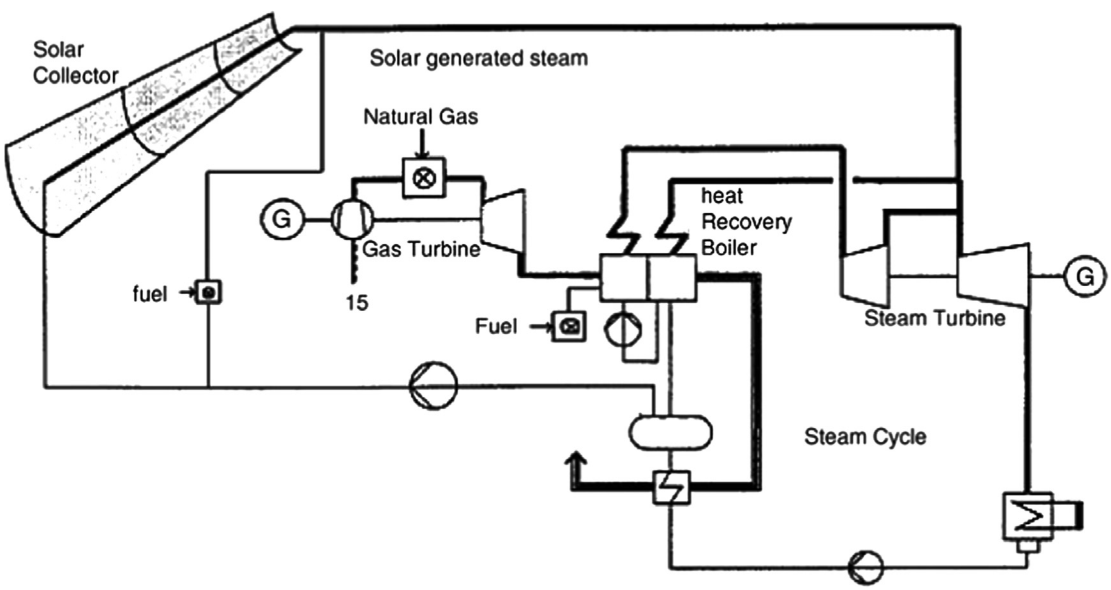

Fig. 15. DSG-ISCCS configuration by El-Sayed [80].

configuration. The component modeling is based on mass and energy balance, whereas thermal and thermodynamic proprieties are estimated using RK-SOAVE and STEAM-TA models. The meteorological parameters including DNI, wind speed and other weather conditions are taken from meteorological year database. The optimization has been revealed that the optimum design pressure and temperature of the reheat and low pressure steam, at design point, are respectively 16 bar and 560 °C, and 5 bar and 320 °C. When compared with one-stage solar input DSG-ISCCS the proposed concept allows the advancement of the net solar-to-electricity efficiency (up to 30%) and overall exergy efficiency (up to 61%) by about 1.2% and 2.5%, respectively. Moreover, it offers higher net electricity efficiency (up to 74%) higher than that of one-stage solar input DSG-ISCC and CC by about 4.5% and 30.9%, respectively. Nevertheless, the overall thermal efficiency of two-stage solar input DSG-ISCCS is lower than that of one-stage (53.4% vs. 54.1%), and therefore, 4E studies are recommended for answering the question about the best DSG-ISCCS configuration that offers the lowest Levelized Electricity Cost.

Integrating DSG technology into the Brayton cycle is a very promising option. Craig et al. [83] have proposed a new ISCCS concept that combines a parabolic tough solar field with a CC power plant, at the level of Brayton cycle. They have proven the feasibility of the proposed concept, which has high reliability and low financial risk according to the authors. It has been observed that the integration of a 100 MW solar thermal energy into 40-MW aero-derivative gas turbine would provide better performance and leads to achieve a solar fraction of about 57–59%.

Livshits and Kribus [84] have introduced a new concept that used solar radiation collected by medium-temperature parabolic trough solar field to enhance the thermodynamic performance of steam-injection gas turbine. As shown in Fig. 17, the proposed

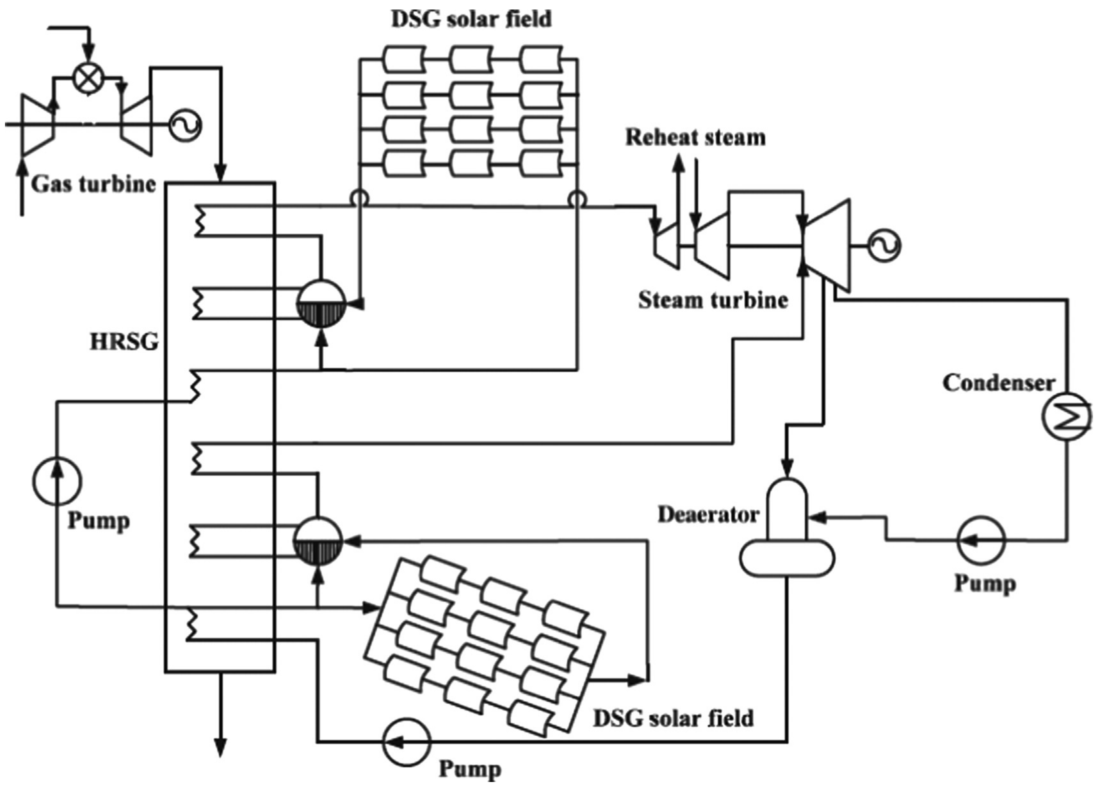

Fig. 16. Advanced DSG-ISCCS with two stage solar input for improving the overall performance [82].

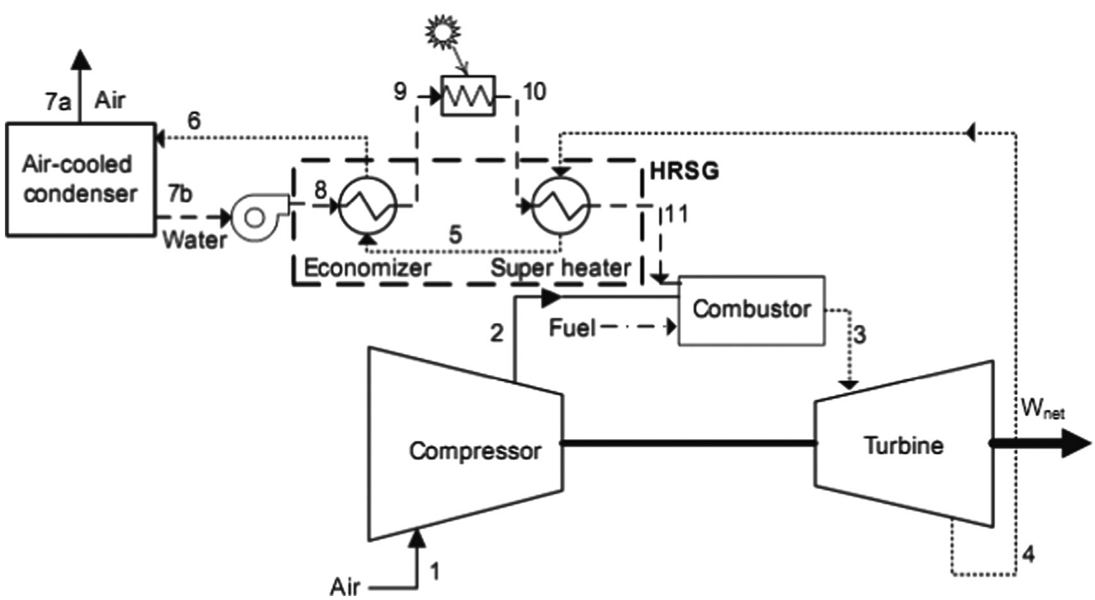

Fig. 17. Solar injected Brayton cycle concept [84].

concept includes the installation of a condenser to recover and recycle the injected-water, and therefore, reduce the water consumption. They have used the Honeywell Unisim process software to simulate the nominal performance of four commercial gas turbines, i.e., Solar centaur 40-T4700 of 3.51 MWe, GE LM2000 of 17.56 MWe, GE LM6000 PC of 43.57 MWe and Mitsubishi 701G of 334 MWe. The overall conversion efficiency, the solar fraction as a function of the steam-to-air ratio, the solar-to-electricity efficiency, the incremental efficiency and the specific water consumption have been investigated. The authors have considered the solar hybrid cycle performance over a wide range of operating parameters, and over a wide range of steam to air mass flow ratio, and has compared them to those of the conventional cycle with the same operational parameters. The simulation results have indicated that overall conversion efficiency of 40–55% is feasible and solar fraction up to 50% can be reached. Furthermore, an incremental efficiency of 22–37%, which correspond to solar-to-electricity efficiency of about 15–24%, similar to and even exceeding current solar power plants are another advantages of the proposed concept.

4.1.3. HTF-ISCCS vs. DSG-ISCCS

Nezammahalleh et al. [85] have made a comparative study between three power plant technologies, i.e., DSG-ISCCS, HTF-ISCCS and HTF-SEGS of similar design data that have been considered by Hosseini et al. [7]. They have found that the DSG-ISCCS has better performance than the two other power plants. Of a particular interest, its LEC has been 2.4% lower than that of HTF-ISCCS due to lower investment costs, higher thermal efficiency and reducing O&M costs. Also, the DSG-ISCCS is capable for saving about 46 million $ in fossil fuels during 30 years lifetime compared to ISCCS-HTF. From the environment point of view, DSG-ISCCS could release about 2.5% points lower GHG emissions than ISCCS-HTF, while the SEGS technology remains the most friendly environmental since it has the lowest CO_2 emissions.

Baghernejad and Yaghoubi [86] have applied multi-objective evolutionary algorithms to determine the optimum solutions that simultaneously satisfy exergetic as well as economic objectives of 400 MW ISCCS in Yazd, Iran. The cases of using air, water or oil as heat transfer fluid in the solar field have been considered and compared. The results have been shown the potential of the proposed optimization technique for improving exergy efficiency by 3.2% while decreasing the cost rate by 3.82%.

Rovira et al. [87] have analyzed and compared DSG-ISCCS and HTF-ISCCS, considering numerous schemes of integrating solar energy into the combined cycle. The CC power plant has been 110 MWe with single 73 MWe gas turbine and dual pressure level HRSG without reheat, while the solar field has been sized to produce 50 MWth. The ISCCS design is shown in Fig. 18. The authors have studied four configurations for each ISCCS technology. These configurations include the use of solar energy for evaporating steam; preheating and evaporating water/steam; evaporating and superheating steam; preheating, evaporating and superheating water/steam. They have also carried out three types of comparisons for all the configurations namely, constant solar fields output of 50 MWth, standardized solar fields, and standardized solar field and steam generator. It has been found that the use of solar energy for steam generation or for both evaporating and superheating steam are more efficient than other options when applied to ISCCS. More in-depth, when compared to HTF-ISCCS it has been observed that DSG-ISCCS which used solar energy to generate steam is the best configuration since it offers the best performance. This has been primarily related to the addition solar steam generator needed in the HTF-ISCCS concept. It has been also observed that the gas turbine, the solar field and the condenser are the major sources of exergy losses.

Horn et al. [88] have technically and economically compared the Trough-HTF-ISCCS with Air-Tower-ISCCS to select the best technology that would be implanted in Egypt. They concluded that the former is more competitive because its LEC of the solar portion is 9.5 US¢/kWh, while the LEC of Air-Tower-ISCCS has been found to be 10.2 US¢/kWh. The environmental analysis has also indicated that HTF-ISCCS power plant produces about 200 t/year of carbon dioxide less then Air-Tower concept. Moreover, about 600,000 t of CO_2 could be avoided, over the power plant lifetime, by implanting and operating such a hybrid solar technology instead of CC technology.

Popov [89] has proposed two novel configurations for comparison to the HTF-ISCCS under the climate of San Bernardino County, CA, US. The solar energy in the proposed configuration is used to power the inlet cooling system of the gas turbine. In the first proposed configuration, shown in Fig. 19a, the gas turbine inlet is equipped with mechanical chiller powered by photovoltaic panels whereas in the second one, as shown in Fig. 19b, the inlet cooling system is accomplished with an absorption chiller supplied with DSG Linear Fresnel solar field. The author has used Thermoflex software and focused on the overall thermal efficiency and the investment cost of the selected plants. The PV system has been designed with System Advisor Model (SAM) software. He has found that the novel configurations offer higher overall thermal efficiency than HTF-ISCCS by more than 1.2% and requires less investment costs. An important finding of this study is that the integration of solar energy into the Brayton cycle provides much more advantages than its integration into the Rankine cycle.

4.2. Coal fired-ISCCS

Coal is formed from vegetation that has been consolidated between other rock strata and altered by the combined effects of pressure and heat over millions of years. Even though, it is considered one of the most pollutant energy source, coal is still the first electricity generation source and it is currently provides about 41% of the world's power needs. Integrating coal with solar offers many advantages particularly the reduction in pollution. In this section we review the schemes that integrate coal fuel with solar energy.

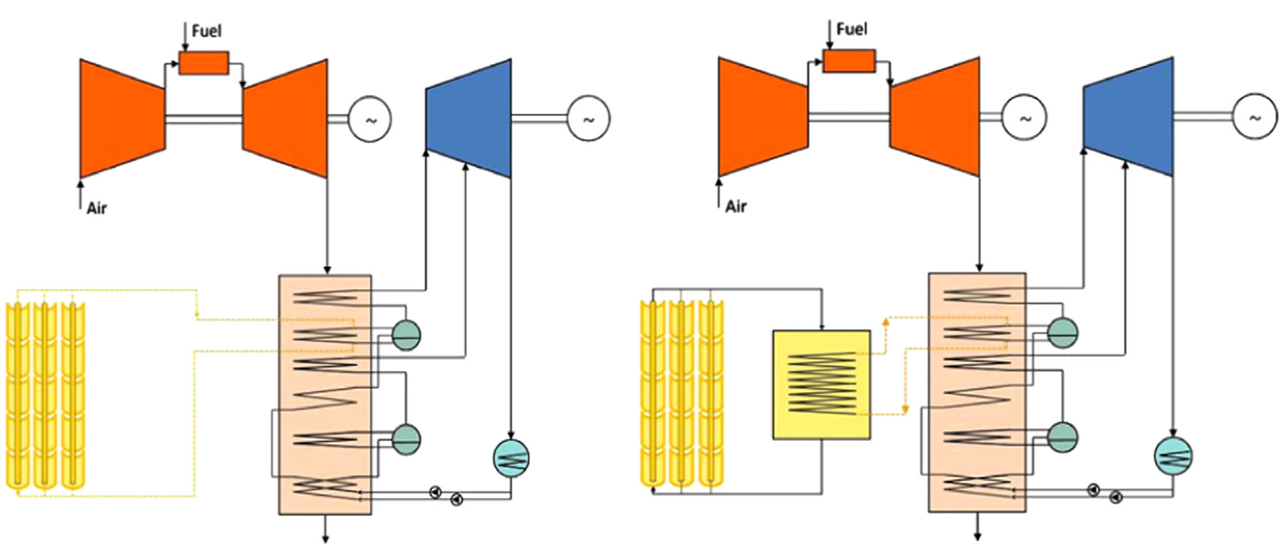

Fig. 18. Comparison between DSG-ISCCS (left) and HTF-ISCCS (right) [87].

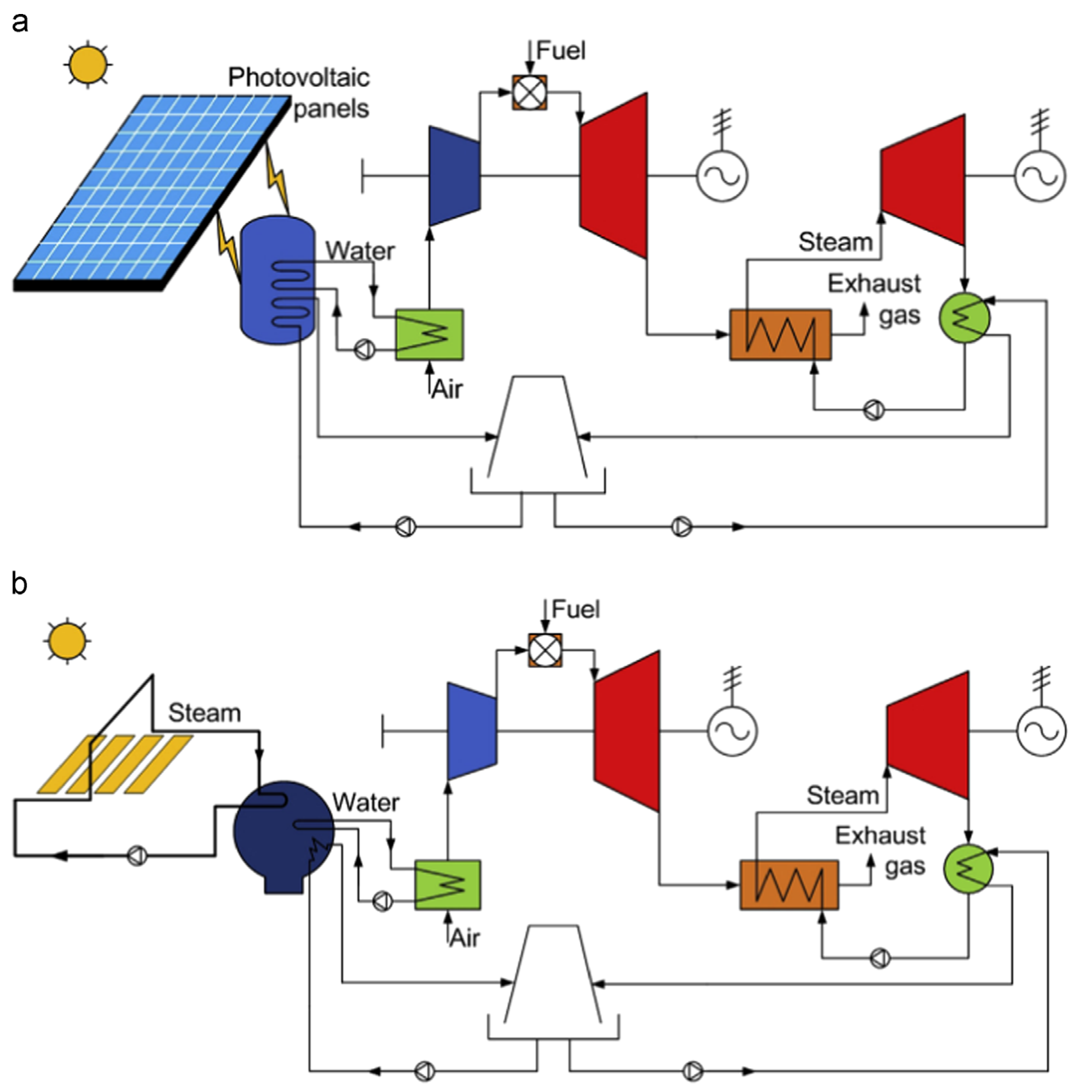

Fig. 19. Two novel ISCCS by Popov [89]. The solar energy is used to power the gas turbine cooling system. (a) A PV panels to work a mechanical chiller for turbine inlet air cooling. (b) A DSG-Fresnel field is used to power an absorption chiller for turbine inlet air cooling.

4.2.1. HTF-ISCCS

Yang et al. [90] have analyzed eight options for integrating thermal energy collected by a parabolic trough solar field into a 200 MW solar aided power generation (SAPG) plant in both power boosting and fuel saving operation modes. For each integration scheme into conventional coal-fired power plant, the bled-off steam is partly or totally replaced by solar thermal energy carried by the Oil-HTF. The authors have found that the solar to electricity efficiency is 36.58% and 25.48% for solar thermal energy respectively at 260 °C and 215 °C.

Peng et al. [91] have focused on the off-design thermodynamic performance of 330 MW solar aided coal-fired power plant. The latter is supposed to be located in Changji City, Sinkiang, China, and the meteorological parameters have been taken from System Advisor Model (SAM) library. The effects of many parameters including the time of the year, HTF mass flow rate and substituted ratio of extracted steam on the plant performance have been investigated in details. Three operational steam turbine loads have been considered in this analysis to examine the effect of load on the net solar-to-electricity efficiency, i.e., 100%, 75%, and 50% of turbine nominal load. The authors have obtained a net solar-to-electricity efficiency peak of 26.3% in summer and observed lower performance of both the steam turbine and the solar field in winter. They have thus suggested two enhancements, namely, changing the tracking mode form North–South axis to East–West axis and combining part-load pattern of turbine with solar heat. These enhancements have introduced significant increase in the performance, i.e., changing the axis would raise the annual net solar-to-electricity efficiency from 20.9% to 22.9%. On the other hand, the second improvement would increase the mean net solar-to-electricity efficiency of the four seasons (on 50% turbine load) from 10.6% to 14.8%. If the two recommendations are implanted then the annual net solar-to-electricity efficiency would get higher from 20.9% to 24.8%. Nevertheless, changing the collectors' axis is really difficult and costly operation so that the gain in performance might not overcome the additional costs related to the operation in question.

Peng et al. [92] have exegetically compared a 330 MW solar aided coal-fired power plant to SEGS and presented a short economic analysis. In order to do so, the well known simulation software ASPEN PLUS has been selected. Based on the energy-utilization diagram method they have analyzed the off-design performance of both plants and found that the hybrid solar aided coal-fired power plant have lower exergy destruction in the solar feed water heater and steam turbine and higher exergy and solar-to-electricity efficiency compared with SEGS. It has also been obtained that the solar exergy efficiency and solar-to-electric efficiency of the hybrid coal-fired power plant are higher than

those of the only solar plant by about 1.3% and 1.4% respectively. The economic assessment has indicated that the Levelized Electricity Cost could be reduced by about 20–30% using the hybrid concept, i.e., from 1.1–1.3 ¥/kWh in SEGS to around 0.8–1.0 ¥/kWh.

4.2.2. DSG-ISCCS

Gupta and Kaushik [93] have compared the performance of 50 kW solar thermal power plant to those of a 220 MW coal fired solar aided thermal power plant. They have found that the performance, in particular the efficiency, of the latter is better than those of the former.

4.2.3. HTF-ISCCS vs. DSG-ISCCS

Suresh et al. [94] have carried out the energy, the exergy, the economic, and the environmental analysis of solar thermal aided coal-fired subcritical (SubC) and supercritical (SupC) steam power plants. They have selected a 500 MWe SubC plant and a 660 MWe SupC power plant, and they have considered two technologies for the solar field, i.e., HTF technology and DSG technology. Figs. 20 and 21 highlight the proposed configurations. The flow-sheet computer program, Cycle-Tempo, has been used for the thermodynamic modeling and analysis. The performance simulation has shown that the substitution of turbine bleed streams with the Solar aided feedwater heating (SAFWH) in both SubC and SupC steam power plants leads to enhancement in fuel consumption by 5–6% and therefore save about 14–19% of coal. From the thermodynamic point of view and based on exergy rather than energy, it has been found that the use of solar thermal energy for feedwater heating is more efficient. Concerning the environment, about 62,000 and 65,000 t of CO_2 could be reduced annually from 500 MWe SubC and 660 MWe SupC coal-fired power plants, respectively. The LEC of SupC power plant without SAFWH, with DSG-SAFWH and with HTF- SAFWH has been found to be 2.33, 2.45, and 2.47 INR/kWh, respectively. For the SubC power plant, these values are respectively 2.26, 2.41 and 2.42 INR/kWh and thus the SubC technology is more competitive than SupC. Furthermore, the DSG is more cost effective than the HTF technology when coupled to coal-fired power plants.

Yang et al. [95] have investigated the performance of various integration options that combine DSG-SF and HTF-SF with a 300 MW solar aided coal-fired power generation (SACPG) plant. They have analyzed each integration scheme and obtained that the solar energy conversion efficiency is higher when it is integrated at higher temperatures. The results have also shown that SACPG is able to save about 4302.8 t/year of coal. Furthermore, its LEC with and without considering environmental costs are respectively 0.098 and 0.011 $/kWh, which is lower than that of SEGS (0.14 $/kWh). The selected design by Yang et al. is illustrated in Fig. 22.

Ordorica-Garcia et al. [96] have presented an overview of three configurations that combine the advantage of CSP technology with

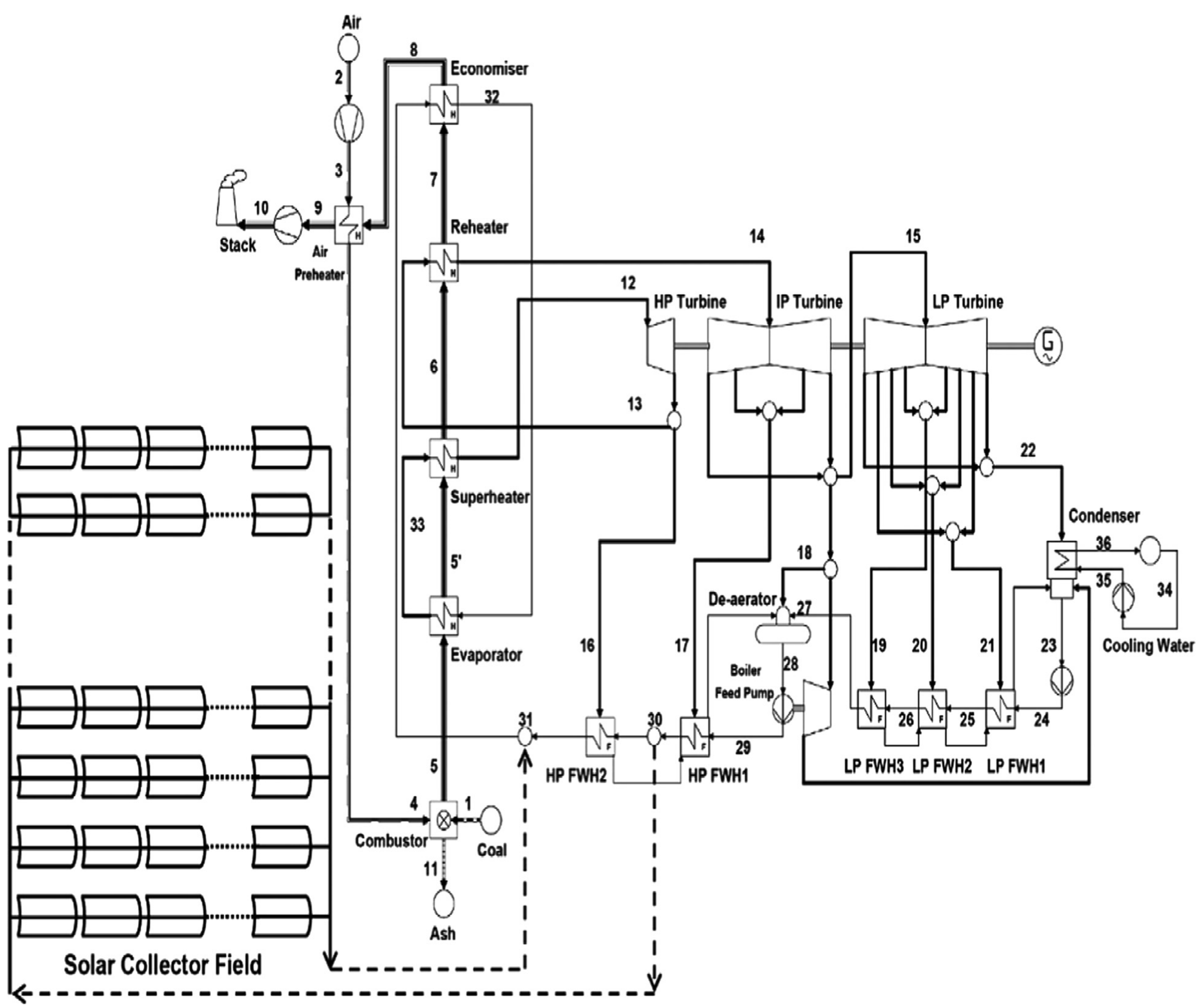

Fig. 20. Coal fired-DSG-ISCCS with subcritical steam cycle [94].

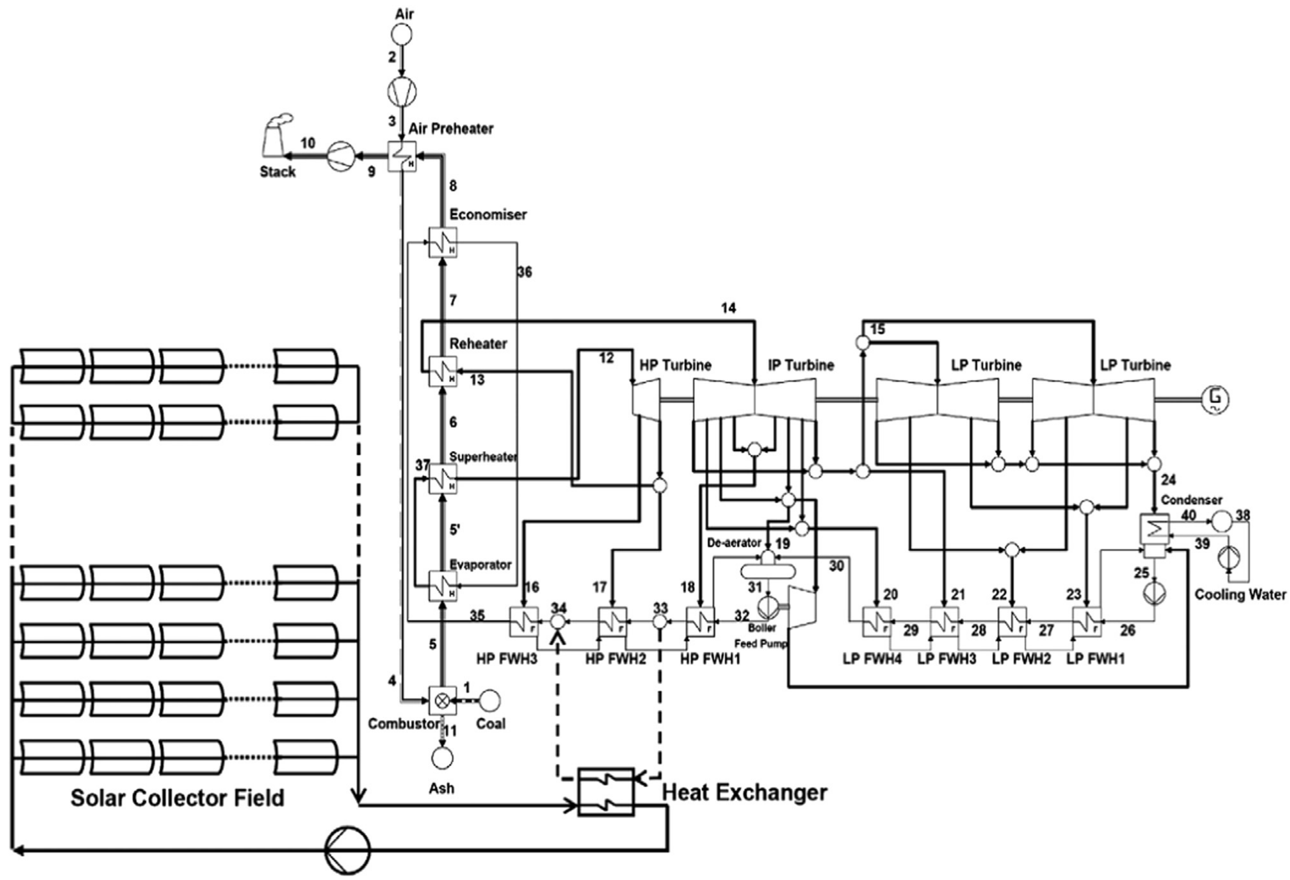

Fig. 21. Coal fired-HTF-ISCCS with supercritical steam cycle [94].

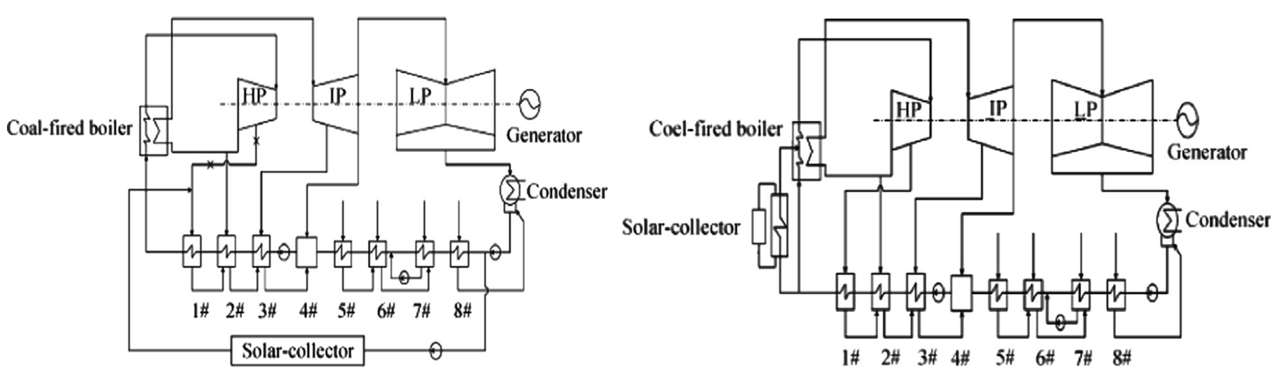

Fig. 22. Comparison between Coal-DSG-ISCCS (left) and coal-HTF-ISCCS (right) [95].

fossil technology, i.e., the ISCCS, Solar-assisted post-combustion capture (SAPCAP), and Solar gasification with Carbon Capture and Storage (CCS). They have presented the basic design, current status and applications of each concept, as well as, their advantages and disadvantages. The authors have paid special attention to the potential of each technology for GHG emissions mitigations.

Davison [97] has focused on the costs and GHG emissions of various fossil fuels power plant technologies integrated with CCS technology, i.e., pulverized coal and natural gas cycles with post combustion capture, coal gasification with intermediate storage of hydrogen-rich gas and coal gasification with PSA hydrogen purification, intermediate storage of hydrogen and post combustion capture. He has concluded that the LEC depends strongly on the fuel costs and CO_2 reduction target. For instance, power plants with CCS such as post combustion capture have the lowest costs when operating at higher capacity factors.

4.3. Renewables-ISCCS

The above ISCCS schemes combine two types of energy sources, i.e., fossils (natural gas) and renewables (solar). These hybrid fossil-solar configurations join the advantages of these energy sources to advance the ISCCS and therefore make them more competitive to today power generation technologies. However, the continuous increase scarcity in fossil fuels together with the upcoming shortage will change the above mentioned schemes, in the long term, into a less competitive one. At this end, hybrid renewable-solar configurations might become the best solution as

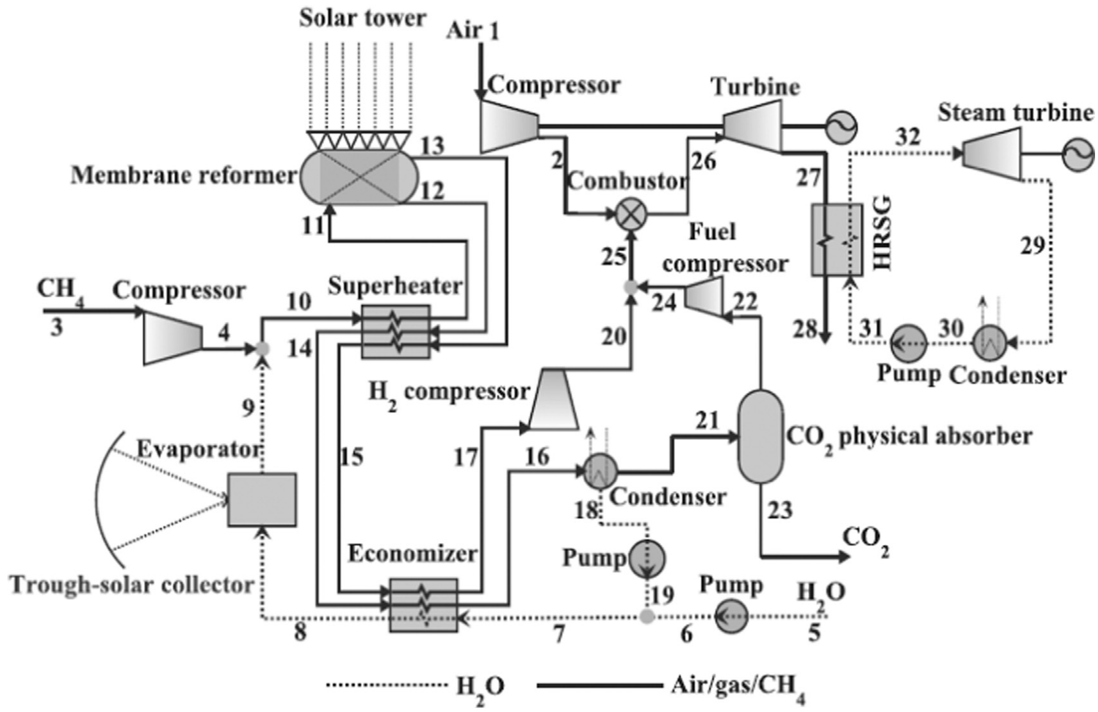

Fig. 23. A novel DGS-ISCCS with CCS [99]. This design uses both the parabolic trough and central receiver technologies to power a thermo-chemical fuel conversion system to produce syngas that is used to power the gas turbine.

the fossil fuels shortage era is going to take a hold. This part highlights the recent studies on renewable-solar ISCCS.

4.3.1. HTF-ISCCS

Rubio-Maya et al. [98] have developed a novel procedure to select and size a poly-generation plant powered by natural gas, solar energy and biomass. The poly-generation plant has been integrated to produce electricity, heat, cold and fresh water. They have used the superstructure concept to determine the most suitable configuration that allows optimum synthesis and design of a poly-generation plant. For optimization purposes, the Mixed Integer Non-linear Programming (MINLP) mathematical techniques have been applied to optimize the energy savings, the greenhouse gases (GHG) emissions of the power plant. The optimization process and the sensitivity analysis have pointed out that poly-generation power plants can provide more advantages when powered by natural gas than renewables. However, the latter have shown higher fuel saving and less GHG emissions than the former which has a strong impact on the electricity prices.

4.3.2. DSG-ISCCS

Li et al. [99] have introduced and analyzed an advanced DSG-ISCCS with solar thermo-chemical fuel conversion and CCS. This advanced DSG-ISCCS is illustrated in Fig. 23. The plant uses both parabolic trough and central receiver technologies for producing syngas that power the gas turbine. The authors have applied ASPEN PLUS software to model the power conversion system while FORTRAN subroutine is used to model the methane reforming system. The performance of the proposed concept has been simulated and compared to those of CC with and without CCS technology. It has been found that the energy and exergy efficiencies of the hybrid system are higher than those of CC with CCS by about 2.2% and 10.2% respectively. Moreover, the concept saves about 31.2% of fuel with a solar thermal share of 28.2%, and the net solar-to-electricity efficiency of about 36.4% compared with the CC-CCS.

Lentz and Almanza [100] have introduced a new hybrid concept that used a DSG-SF to enhance the performance of 100 WM geothermal plant located in Cerro Prieto, Mexico, and therefore, to prevent silica deposition in the geothermal process. The proposed concept has consisted of a geothermal well, a DSG solar field, flash separator, steam turbine and condenser. To increase the enthalpy and the steam quality of Cerro Prieto well of 1566 kJ/kg, a 9250 m^2 DSG-SF with a flow of 25.67 kg/s has been proposed. The authors have examined three different options for integrating solar energy into a geothermal power plant. The first scheme consists in the installation of DSG-SF between the wells and the first steam separator, while in the second one the solar field is located between the first and the second steam separators. In the third suggested scheme water leftover from the cooling towers is used to produce steam in the solar field. This latter is the most preferred because it decreases the total salinity and it causes less scaling on the pipes from the wells.

4.3.3. HTF-ISCCS vs. DSG-ISCCS

Jamel et al. [101] have briefly reviewed some studies and published papers that have focused on integrating solar thermal energy with fossils and renewables power plants including hybrid solar–steam cycle power plants, integrated solar combined-cycle systems (ISCCS), hybrid solar–gas turbine power plants and hybrid solar–geothermal power plants. The authors have asserted that fossil fuels and climate changes effects, as well as, technical and economic advantages of the previous power cycles are the major drivers of hybrid solar thermal power plants. Due to its maturity and the larger capacity implementation around the world, it has been pointed out that ISCCS with parabolic trough technology is more preferred compared to that with central receiver technology.

Peterseim et al. [102] have investigated 17 different configurations of biomass-CSP plants to find out the best configuration taking into account the technical, economic, and environmental

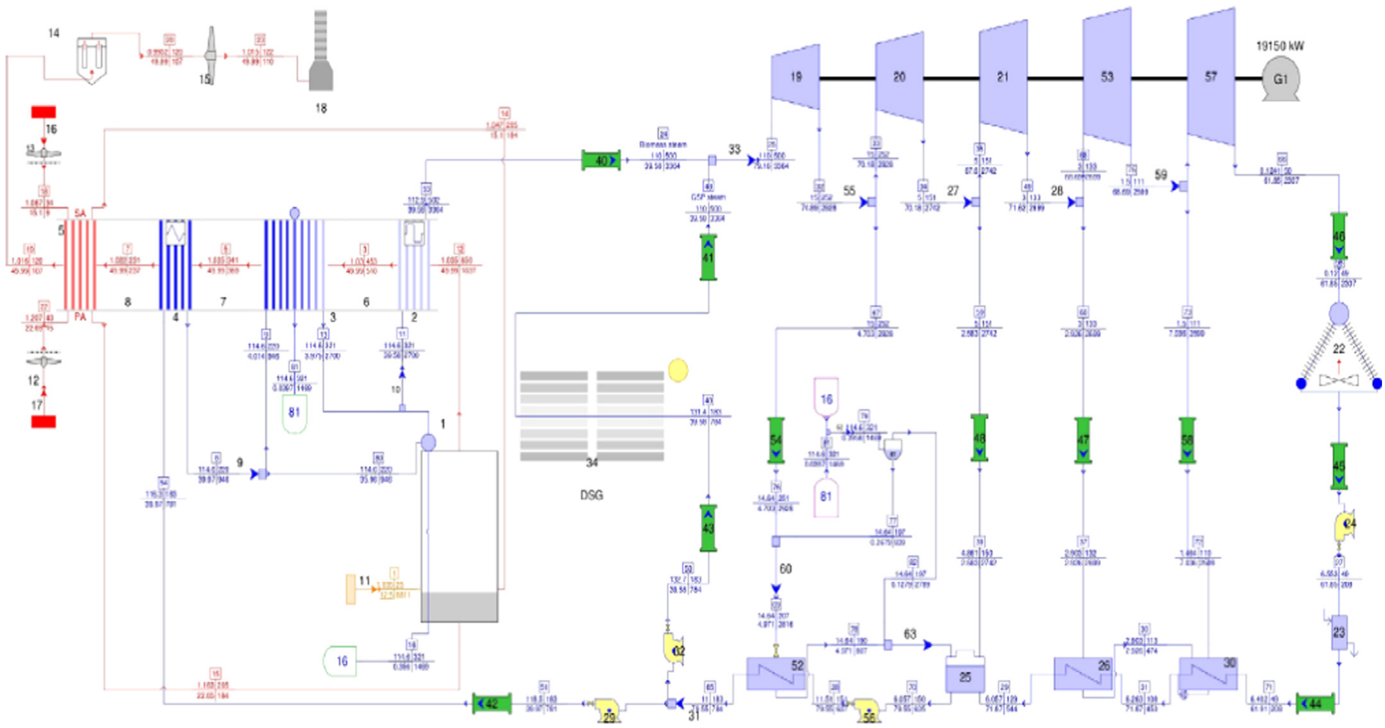

Fig. 24. Hybrid Biomass-CSP plant with biomass/waste materials [102].

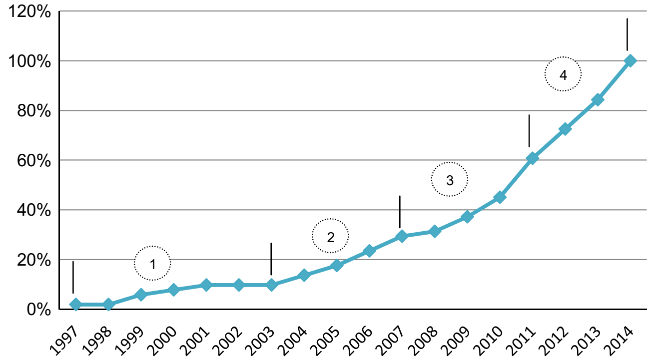

Fig. 25. Progress in R&D activities for advancing the ISCCS.

performance. Seven of the proposed configurations use the parabolic trough technology. The site selected for this analysis is near Mildura, Australia. The well known software Thermoflex has been used to evaluate biomass-CSP hybrid concepts that have more than 5 MWe reference plants. A typical configuration of a biomass-CSP plant is reported in Fig. 24. It has been shown that a parabolic trough hybrid plant with salt-HTF and biomass gasification technology could reach thermal efficiency up to 33%, ensures specific cost reduction of 5% and has internal rate of return on investment around 9.1%, while the central receiver remains the best choice. This study has indicated that salt-HTF technology offers better performance than the DSG. For instance, the thermal efficiency when using the former could be about 2.4% higher than when using the latter.

5. Analysis and comparison

This section summarizes the above reviewed studies and provides in-depth analysis. The analysis includes the evolution in the R&D activities since the introduction of the ISCCS concept and discusses the most important finding. The section also reviews the tools, techniques and software that have been used or developed to perform the ISCCS with a parabolic trough technology.

5.1. Progress in R&D activities

R&D in hybrid solar thermal power plants is strongly related to fossil fuel prices and energy policy [30,74]. For the so called, ISCCS that offers the most economic way for converting solar energy into electricity, R&D activities have been raising rapidly since the introduction of such a concept by Allani et al. in 1997. Fig. 25 illustrates the evolution of published papers that focus on the ISCCS including its feasibility assessment and the 4E (energy, exergy, economy, environment) analysis as well as technical studies. We consider the total published papers up to now as a unity (100%), so that we can present the ratio of the number of published papers in each year. It is obvious that the interest in the integrated solar combined cycle system with a parabolic trough technology increases exponentially, except for the year 2003, when no article has been published. More in-depth, we have observed four phases in the progress of R&D activities. In the first phase, from 1997 to 2003, a logarithmic growth in the R&D is observed. During this period of seven years, the R&D activities have been in the early stage and therefore few studies have been published. This is due to the lower prices of fossil fuels, the high cost of solar systems and the lack of government supports in form of feed-in-tariffs and taxes release. The integration of solar energy into the combined cycle has been the focus of the published studies with the aim of finding out the most suitable ISCCS configuration. It has been found that the best configuration uses solar energy for generating steam to power a Rankine cycle.

In the second phase, from 2003 to 2007, the interest in the ISCCS starts to rise dramatically and exponentially. During only four years the fraction of published papers has reached 40% (about three times more than the first phase). This increase has been boosted by government supports and by the introduction of

national and international renewable energies programs in many developed and developing countries. Moreover, huge initiatives in particular Desertec have opened the door for such advanced concept to be more competitive. The rise in fossil fuels costs has also been an important player in this phase. The authors have focused on the 3E (energy, economy, environment) assessment. From the energy point of view, the results have revealed that the ISCCS can offer a lot of advantages compared with other power plant technologies such as Solar Electric Generating System (SEGS) and simple gas turbine, while the CC remains the best large scale power generation technologies.

In the third phase, from 2008 to 2010, the interest has boomed once more. Advanced assessment techniques such as exergy and exergeo-economic analysis have been introduced. In this period, many projects were under construction or under development in Middle East and North Africa (MENA) region, particularly in Algeria, Morocco and Egypt. These ISCCSs have relatively smaller solar field since it has been proven that the most economic and efficient plant corresponds to smaller solar field.

The last phase starts from 2011 and coincides with the inauguration of numerous ISCCSs such as Beni Mathar, Hassi R'Mel and Kuraymat. It has also confirmed the maturity of the ISCCS concept. In 2011, 20% of the total papers have been published. Therefore, experiments are the most drivers of R&D activities [4].

In 2014, we have observed that some countries, such as China, have recently expressed interest and have significantly supported R&D activities on hybrid solar thermal power plants. The number of published studies is a good indicator for that.

Table 8
Summary of published studies on the ISCCS.

Authors	Plant technology	Country selected	Case study	Integration cycle	Investigation				
					En.	Ex.	Eco.	Env.	Tec.
Allani et al. [48]	NG_HTF-ISCCS	Tunisia	PAESI	ST				+	
Kane and Favrat [49]	NG_HTF-ISCCS	Tunisia	PAESI	ST	+				
Kane and Favrat [50]	NG_HTF-ISCCS	Tunisia	PAESI	ST	+				
Kane et al. [51]	NG_HTF-ISCCS	Tunisia	PAESI	ST	+	+			
Hosseini et al. [52]	NG_HTF-ISCCS	Iran	–	ST	+	+	+		
Baghernejad and Yaghoubi [53]	NG_HTF-ISCCS	Iran	Yazd ISCCS	ST	+	+			
Baghernejad and Yaghoubi [54]	NG_HTF-ISCCS	Iran	Yazd ISCCS	ST		+	+		
Baghernejad and Yaghoubi [86]	NG_HTF-ISCCS vs. NG_DSG-ISCCS	Iran	Yazd ISCCS	ST		+	+		
Khaldi [57]	NG_HTF-ISCCS	Algeria	Hassi R'Mel ISCCS	ST	+	+			
Derbal al. [58]	NG_HTF-ISCCS	Algeria	Hassi R'Mel ISCCS	ST	+				
Behar et al. [59,60]	NG_HTF-ISCCS	Algeria	Hassi R'Mel ISCCS	ST	+				
Elhaj et al. [61]	NG_HTF-ISCCS	Lybia	–	ST					
Elhaj et al. [62]	NG_HTF-ISCCS	Lybia	–	ST	+				
Elhaj et al. [63]	NG_HTF-ISCCS	Lybia	–	ST		+			
Elsaket [81]	NG_DSG-ISCCS	Libya	–	ST	+			+	
Brakmann et al. [68]	NG_HTF-ISCCS	Morocco	Beni Mathar	ST					+
Brakmann [69]	NG_HTF-ISCCS	Morocco, Egypt	Beni Mathar, Kuraymat	ST					+
Brakmann et al. [67]	NG_HTF-ISCCS	Egypt	Kuraymat	ST					+
El-Sayed [80]	NG_DSG-ISCCS	Egypt	Kuraymat	ST	+		+		
Horn et al. [88]	NG_HTF-ISCCS vs. NG_DSG-ISCCS	Egypt	–	ST	+		+	+	
Popov [89]	NG_DSG-ISCCS	US	–	GT	+		+		
Turchi and Ma [71]	GN_HTF-ISCCS	US	–	ST	+		+		
Antoñanzas-Torres et al. [70]	NG_HTF-ISCCS	US, Spain	–	ST	+				
Montes et al. [78]	NG_DSG-ISCCS	US, Spain	–	ST	+		+		
Franchini et al. [65]	NG_HTF-ISCCS	Spain	–	ST	+				
Montes et al. [79]	NG_DSG-ISCCS	Spain	–	ST	+				
Peng et al. [92]	Coal_HTF-ISCCS	China	–	ST	+	+	+		
Peng et al. [91]	Coal_HTF-ISCCS	China	–	ST	+				
Li and Yang [82]	NG_DSG-ISCCS	China	–	ST	+	+			
Siva Reddy et al. [66]	NG_HTF-ISCCS	India	–	ST			+		+
Bakos and Parsa [64]	NG_HTF-ISCCS	Greece	–	ST	+		+		
Lentz and R. Almanza [100]	RE_DSG-ISCCS (geothermal)	Mexico	–	ST	+				
Dersch et al. [72]	NG_HTF-ISCCS	–	–	ST	+		+		
Reddy et al. [80]	NG_HTF-ISCCS	–	–	ST	+	+			
Kelly et al. [74]	NG_HTF-ISCCS	–	–	ST	+				
Cau et al. [76]	NG_HTF-ISCCS	–	–	ST	+		+		
Craig et al. [83]	NG_DSG-ISCCS	–	–	GT	+				
Livshits and Kribus [84]	NG_DSG-ISCCS	–	–	GT	+				
Peterseim et al. [102]	RE_ISCCS (biomass)	–	–	ST	+		+		+
Al-Sulaiman [77]	NG_HTF-ISCCS	–	–	ST	+	+			
Li et al. [99]	RE_DSG-ISCCS (hydrogen)	–	–	GT	+	+		+	
Gunasekaran et al. [75]	NG_HTF-ISCCS	–	–	ST	+				
Nezammahalleh et al. [85]	NG_HTF-ISCCS vs. NG_DSG-ISCCS	–	–	ST	+		+	+	
Rovira et al. [87]	NG_HTF-ISCCS vs. NG_DSG-ISCCS	–	–	ST	+	+			
Yang et al. [90]	Coal_HFT-ISCCS	–	–	ST	+				
Gupta and Kaushik [76]	Coal_DSG-ISCCS	–	–	ST	+				
Suresh et al. [94]	Coal_HTF-ISCCS vs. Coal_DSG-ISCCS	–	–	ST	+	+	+	+	
Yang et al. [95]	Coal_DSG-ISCCS vs. Coal_DSG-ISCCS	–	–	ST	+		+		
Ordorica-Garcia et al. [96]	Coal_HTF-ISCCS vs. Coal_DSG-ISCCS	–	–	ST					+
Davison [97]	Coal_HTF-ISCCS vs. Coal_DSG-ISCCS	–	–	ST			+	+	
Rubio-Maya et al. [98]	RE_HTF-ISCCS (biomass)	–	–	ST	+		+	+	
Jamel et al. [101]	HTF-ISCCS vs. DSG-ISCCS	–	–	GT, ST					

(–) Not available/not considered, (+) paper focus, (ST) Steam Turbine, (GT) Gas Turbine, (NG) Natural Gas, (RE) REnewable, (DSG) Direct Steam Generation, (HTF) Heat Transfer Fluid, (En.) Energy, (Ex.) Exergy, (Eco.) Economy, (Env.) Environment, and (Tec.) Technical.

5.2. Published papers summary

Table 8 summarizes the focus of R&D activities and published papers. Most researchers have selected Sahara desert for their investigations (Algeria, Egypt, Libya, Morocco, and Tunisia). Others have chosen Iran, the US, Spain, Mexico, and very recently China. This is due to the huge potential of these regions in solar radiation and fossil resources, which support the hybrid power plant implantation. This is also supported by operational, under construction and planned ISCCS in the above countries. We have scrutinized the reviewed papers and we found very interesting results. Since the parabolic trough technology is not able to grant higher operation temperatures, the solar energy has been used to generate saturated steam to power the Rankine cycle or to improve the Brayton cycle performance. More than 95% of the authors have considered the integration of Parabolic Trough Technology (PTT) into modern steam turbines. Various Rankine cycles have been investigated including simple pressure level, double pressure levels, three pressure levels, as well as, subcritical and supercritical cycles that are very promising to improve the efficiency and therefore bring the ISCCS technology to be more competitive. Nevertheless, the integration of solar energy into Brayton cycle has been recently proposed for enhancing the performance of solar hybrid steam injection gas turbine. The performance analysis has already proved the potential of such a concept, especially when combined with low-cost solar collectors.

Many authors have focused on the prediction of the performance of the ISCCS power plants. Since the launch of some projects like Yazd and Hassi R'mel, technical assessments have taken place. Comparative studies have also been interesting. This includes the comparison of the ISCCS to other power plant technologies such as GT, CC, SEGS and central receiver system (see Table 9). Results have confirmed the competitiveness of the ISCCS with a parabolic trough technology.

Table 8 also clearly shows that many researchers have selected operational, under construction, planned or announced integrated solar combined cycle power projects as a case study. Yazd and Hassi R'Mel ISCCSs have been well studied and some in-depth analyses have been carried out particularly for the former.

As shown in Fig. 26, it has also been observed that most of ISCCSs have been using natural gas for hybridization. About 75% of the total published papers have considered the natural gas (NG). This is because of its lower costs compared with other fossil fired fuels. Besides, natural gas is the cleanest fossil sources and it allows the achievement of higher performance compared with coal. When compared with the friendly environmental renewable sources such as biomass and geothermal, natural gas offers the most economic and efficient options and therefore support the development and the competitiveness of the ISCCS technology.

The three above mentioned energy sources, i.e., natural gas, coal and renewable, have already been used or proposed for hybridizing the ISCCS. Fig. 26 also indicates that there is less interest in the integration of solar energy into a coal fired combined cycle power plant. This is certainly related to its environmental effects and the higher investment costs of the coal-ISCCS compared with NG-ISCCS.

There is also less interest in the hybridization of ISCCS with renewables. No more than 9% has been found from the total published papers. This is due to their higher costs and the higher the cost of the hybrid source the higher is the LEC and therefore the less is the competitiveness of the ISCCS.

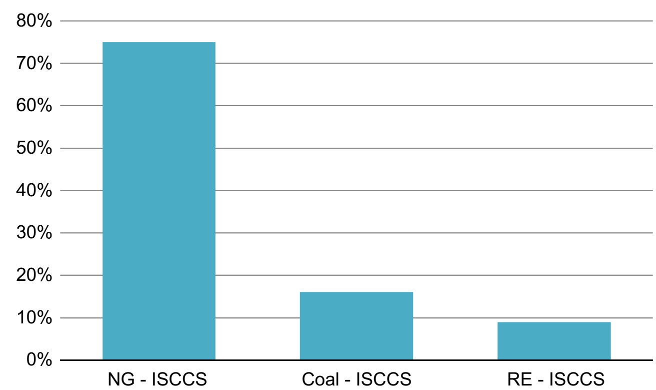

Fig. 26. Authors' focus in the ISCCSs.

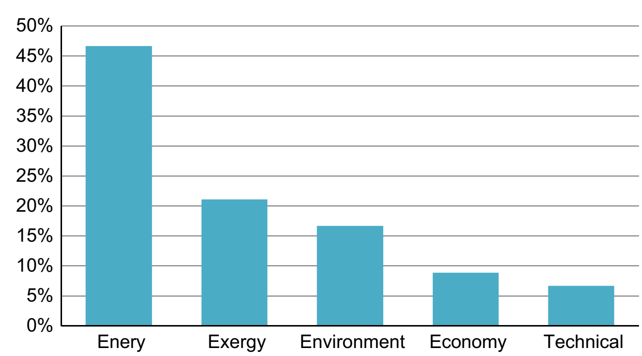

Fig. 27. Subject of published papers on ISCCS.

Table 9
Comparison of ISCCS to other thermal power plants.

Authors	Considered power plants	Which is the best power plant technology			
		Energy	Exergy	Economy	Environment
Hosseini et al. [52]	ISCCS, CC, SEGS, GT	CC	CC	CC	SEGS
Franchini et al. [65]	Trough-ISCCS, Trough-SEGS, Tower-ISCCS, Tower-SEGS	Tower-ISCCS	Tower-ISCCS	Trough-ISCCS	Tower-ISCCS
Antoñanzas-Torres et al. [70]	ISCCS, CC	CC	CC	CC	ISCCS
Turchi and Ma [71]	ISCCS, ISCCS-TES, SEGS, GT	ISCCS-TES	ISCCS-TES	ISCCS-TES	ISCCS-TES
Dersch et al. [72]	ISCCS, SEGS, CC	CC	CC	CC	SEGS
Reddy et al. [73]	ISCCS, CC	CC	CC	CC	ISCCS
Cau et al. [76]	ISCCS, CC	CC	CC	CC	ISCCS
Montes et al. [78]	ISCCS, CC	CC	CC	CC	ISCCS
Li and Yang [82]	2 Stage-ISCCS, one stage-ISCCS, CC	2 Stage-ISCCS	2 Stage-ISCCS	CC	2 Stage-ISCCS
Livshits and Kribus [84]	ISCCS, CC	CC	CC	CC	ISCCS
Nezammahalleh et al. [85]	ISCCS, SEGS	ISCCS	ISCCS	ISCCS	SEGS
Horn et al. [88]	ISCCS, CRS	ISCCS	ISCCS	ISCCS	ISCCS
Popov [89]	PV-ISCCS, Fresnel-ISCCS, trough-ISCCS, CC	CC	Trough-ISCCS	CC	PV-ISCCS
Yang et al. [95]	ISCCS, SEGS	ISCCS	ISCCS	ISCCS	SEGS
Li et al. [99]	ISCCS-CCS, CC-CCS, CC	CC	CC, ISCCS-CCS	CC	ISCCS-CCS

In order to reduce the LEC of the ISCCS, the authors have proposed the use of DSG technology. The present review has revealed that the DSG technology is better than HTF technology, when applied for the ISCCS. Sections 4.1.3–4.3.3 are wealthy of comparisons between the DSG-ISCCS and HTF-ISCCS power plants.

5.3. Key R&D finding and comparison

R&D activities are one of the major drivers for technology enhancement and cost reduction of CSP plants [12]. Fig. 27 illustrates the subject of the published studies including energy, exergy, economy, environment and technical analysis. About a half of the published papers deals with energy analysis because it is an important tool for predicting the efficiency of the ISCCSs and comparing it to those of GT, CC, SEGS, and Central Receiver System (CRS). An essential finding of the energy analysis has been the performance of ISCCSs in the Sunbelt countries of Hot-Dry climate. It has been found that the ISCCS concept is capable of offering better performance than the combined cycle power plant. Moreover, the higher the solar radiation intensity and therefore the ambient temperatures the better is the performance of the ISCCS than those of CC, GT and SEGS.

From the economic point of view, it has been found that the LEC of ISCCS is lower than that of SEGS and the lowest is that of the CC power plant. Besides, progress in R&D and the continuous rise in fossil fuels prices would bring the ISCCS to be the best choice in the near future. Table 9 illustrates a comparison between the well known power plant technologies. It has been observed that most of the authors have considered the combined cycle as a reference power plant in their investigation since it is the most economic and the most efficient power technology up to now. It has been found that the parabolic trough technology still offers lower LEC than the CRS. From the environmental point of view, the only solar power plant, like SEGS, has shown the potential to reduce climate change and GHG emissions. Also, the ISCCS is more advantageous than the combined cycle for reducing climate hazards in particular if decisive actions will be taken.

The exergy analysis is an important tool for improving power plant performance and locating weaknesses. It has been shown that interest in this kind of investigation has been rising sharply because of its key finding compared with energy analysis. The energy and exergy analysis have been revealed that the combustor of the gas turbine is the major part of exergy losses followed by the solar field, while major energy losses take place in the condenser and the stack. Table 10 provides the major inefficient components. So that, many R&D efforts should be focused on these parts for improving their performance and therefore enhancing the ISCCS.

5.4. Tools and techniques applied for advancing the ISCCS

Before implanting any R&D project, the researchers are commonly used simulation tools. The simulation tools which include

Table 10
Energy and exergy analysis for locating weaknesses and therefore future R&D activities.

Authors	Main energy losses		Main exergy losses	
Baghernejad and Yaghoubi [53,54,56]	Condenser	Stacks	Combustor	Solar field
Khaldi [57,63]	Condenser	Solar field	Condenser	Solar field
Siva Reddy et al. [73]	Condenser	HRSG	Combustor	HRSG
Al-Sulaiman [77]	Solar field	Evaporator	Solar field	Evaporator

Table 11
Software used by the authors.

Authors	Software and/or model
Dersch et al. [72]	GateCycle
Kelly et al. [74]	GateCycle
Cau et al. [76]	GateCycle in addition to a new model for developed for the solar field.
Derbal-Mokrane et al. [58]	TRNSYS-STEC
Bakos and Parsa [64]	TRANSYS-STEC
Franchini et al. [65]	TRANSYS-STEC, Thermoflex
Montes et al. [78]	TRANSYS-STEC
Turchi and Ma [71]	IPSEpro, SAM, Excel
Popov [89]	Thermoflex, SAM
Peterseim et al. [102]	Thermoflex
Gunasekaran et al. [75]	ASPEN PLUS/ CUSTOM
Li et al. [99]	ASPEN PLUS, FORTRAN
Li and Yang [82]	ASPEN PLUS
Peng et al. [92]	ASPEN PLUS
Suresh et al. [94]	Cycle-Tempo
Khaldi [57]	Cycle-Tempo
Livshits and Kribus [84]	Honeywell Unisim process
Antoñanzas-Torres et al. [70]	A new model developed by authors implanted in SAM, Meteonorm
Siva Reddy et al. [73]	A new model developed by authors implanted in EESS
Behar et al. [59]	A new model developed by authors implanted in Fortran
Elsaket [61]	A new model developed by author implanted in Fortran
Elhaj et al. [81]	A new model developed by authors implanted in Fortran, Desalsolar, CATT2
Baghernejad and Yaghoubi [54]	A new model developed by authors implanted in Matlab
Kane and Favrat [49]	A new model developed by authors
Kane and Favrat [50]	A new model developed by authors
Kane et al. [51]	A new model developed by authors
Rubio-Maya et al. [98]	A new model developed by authors
Al-Sulaiman [77]	A new model developed by authors implanted in EESS

Table 12
Mathematical techniques used for advancing the ISCCS.

Authors	Applied techniques	Purposes
Kane and Favrat [49]	Pinch technology approach with a thermodynamic modeling technique	Optimizing steam turbine parameters
Kane et al. [51]	Pinch technology approach with a mathematical programming algorithm	Solving the pinch point issue
Baghernejad and Yaghoubi [54]	Eexergo-economic principles and genetic algorithms	Optimizing exergy and costs
Baghernejad and Yaghoubi [86]	Multi-objective evolutionary algorithms	Optimizing exergy and costs
Rubio-Maya et al. [98]	Mixed Integer Non-linear Programming (MINLP) mathematical techniques	Optimizing performance

codes and software have been applied for predicting the performance of energy systems, and consequently, reducing investment risks. The in-depth analysis of the reviewed papers has revealed that most of the authors have developed their own tools for predicting the performance of the ISCCSs with a parabolic trough technology. This is because such a technology is recently introduced and therefore there has been a lack of efficient and powerful tools for simulation the whole ISCCS. However, similar efforts will support the development of advanced codes and software. It has been observed that MATLAB and FORTRAN are widely used by the authors due to their higher potential in modeling and simulation.

Since there are minor tools for predicting the performance of the overall plant, a number of authors have investigated the major components of the ISCCSs. For simulating the power conversion system (PCS) which includes the gas turbine and the steam turbine, some authors have used GateCycle and Cycle-Tempo (see Table 11). These softwares simulate the performance of the PCS based on mass and energy balances. They also include off-design performance. A graphical user interface can be used to construct the PCSs and enter data similar to that of TRNSYS. This latter has been applied to model different transient ISCCSs behavior using modular components. In addition to the above software, the Solar Adviser Model (SAM) that combines hourly simulation models with performance, cost, and finance models to estimate the output, costs, and cash flows, has been also applied for investigating the ISCCS. Very recently two powerful software packages have been adapted to be able to simulate the overall ISCCS configuration, namely ASPEN PLUS and Thermoflex. For this reason, latest published studies have used these software packages.

For the optimization purpose, it has been observed that many mathematical techniques and approaches have been employed. Kane et al. have coupled a pinch technology with a thermodynamic modeling technique to optimize the pressures levels and temperatures of the Rankine cycle. Moreover, pinch technology approach has been applied together with a mathematical programming algorithm for minimizing the pinch point affected by the integration of a parabolic trough solar field into a modern combined cycle power plant. Baghernejad and Yaghoubi have focused on the exergy and costs analysis of the ISCCS and they have found promising results. Thanks to genetic algorithms and multi-objective evolutionary algorithms that are applied for maximizing the efficiency and minimizing costs. The applied techniques and their objectives are outlined in Table 12.

6. Conclusion

In the present paper, the integrated solar combined cycle system with a parabolic trough technology has been reviewed. The status of operational, under construction and planned power plants has been highlighted, the major results of R&D activities and published studies summarized and a detailed analysis provided. We have observed an exponential increase in the R&D activities and in the implantation of the ISCCSs. Various configurations have been proposed and their performance investigated. These include hybridization of solar energy with natural gas, coal and renewables like biomass and geothermal. Most of the reviewed studies have considered the integration of solar energy at the level of the Rankine cycle. Other advanced concepts that integrated a parabolic trough solar field into a Brayton cycle have been recently introduced. Namely, the solar steam injected gas turbine that shows a great potential for improving the solar electricity ratio.

It has been observed that there is a great interest in the development of hybrid natural gas solar combined cycle NG-ISCCS and more particularly in the DSG-ISCCS technology. The authors have found that the DSG-ISCCS offers better performance than the state of the art, HTF-ISCCS. Modeling and simulation using powerful tools and techniques have shown that the use of DSG concept would lead to about 3% reduction in LEC due to lower investment and O&M costs and higher thermal efficiency. Furthermore, the DSG-ISCCS is capable of saving a hundred million dollars of fossil fuels worth during its lifetime compared to HTF-ISCCS. From the environment point of view, the DSG concept allows the reduction of about 2.5% in GHG emissions, while the SEGS remains the most environmental parabolic trough solar thermal power plant technology up to now.

From the present review study, it has been found that

- the higher the solar field performance the higher the operating temperature and thus the higher the efficiency;
- the smaller the solar field the higher the exergy efficiency;
- the higher the steam pressure level and the more the feed water heaters the higher are steam cycle performance;
- the larger the power plant the lower the produced electricity cost;
- the higher the fossil fuel prices the more the competitiveness of the ISCCS.

The rapid advances in ISCCS R&D activities have permitted the development of very efficient and cost effective configurations. Taking into account this fact and with the continuous drop in fossil fuel resource reserves and rise in their prices, ISCCS is becoming more competitive to conventional combined cycle power plants. It could then be the technology of choice in the near future.

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